NEW

Deadly frog skin

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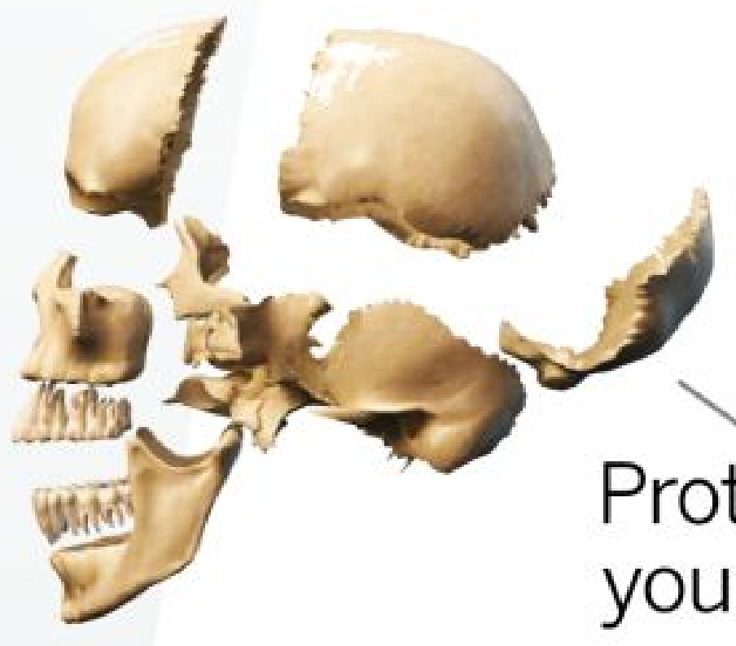
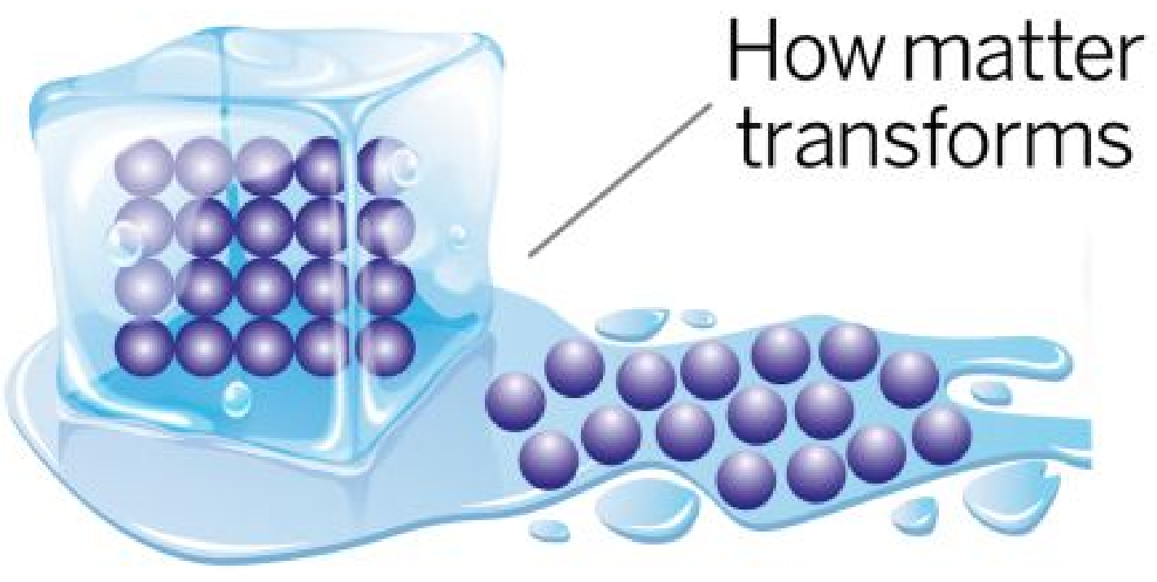

Protecting your brain


How matter transforms

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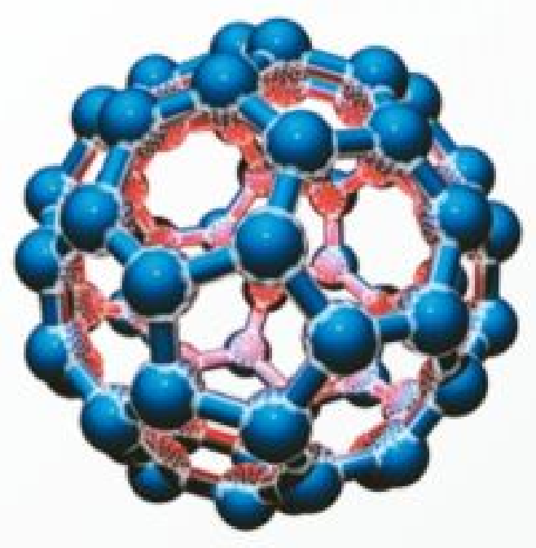
World-changing wonder materials

Our complex neuronal networks

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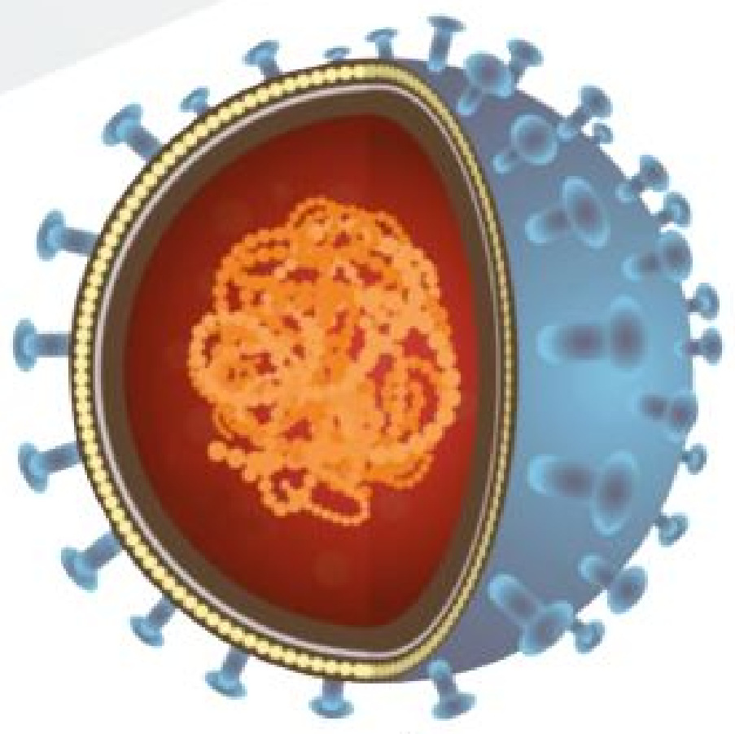
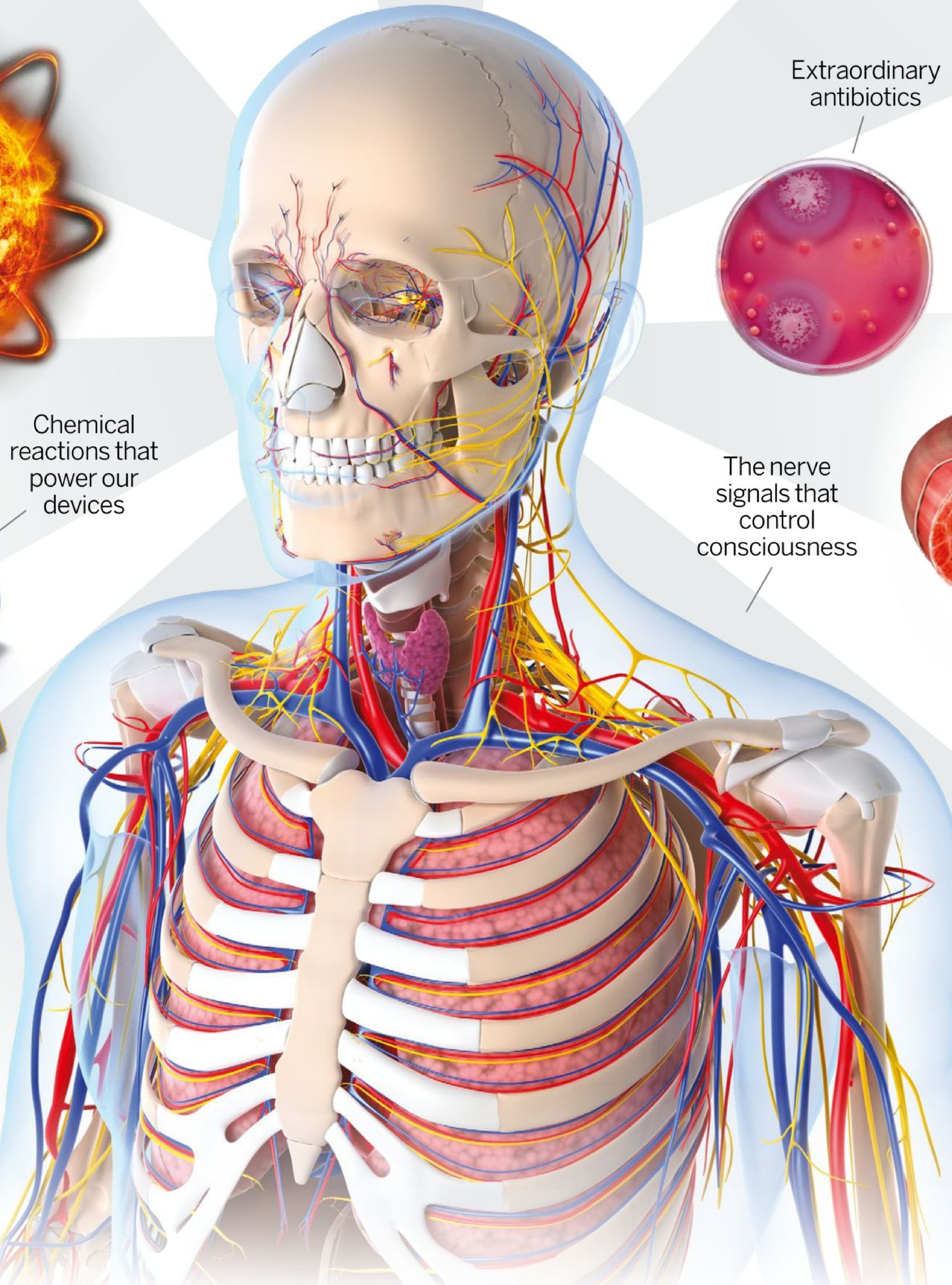
The physics of fusion

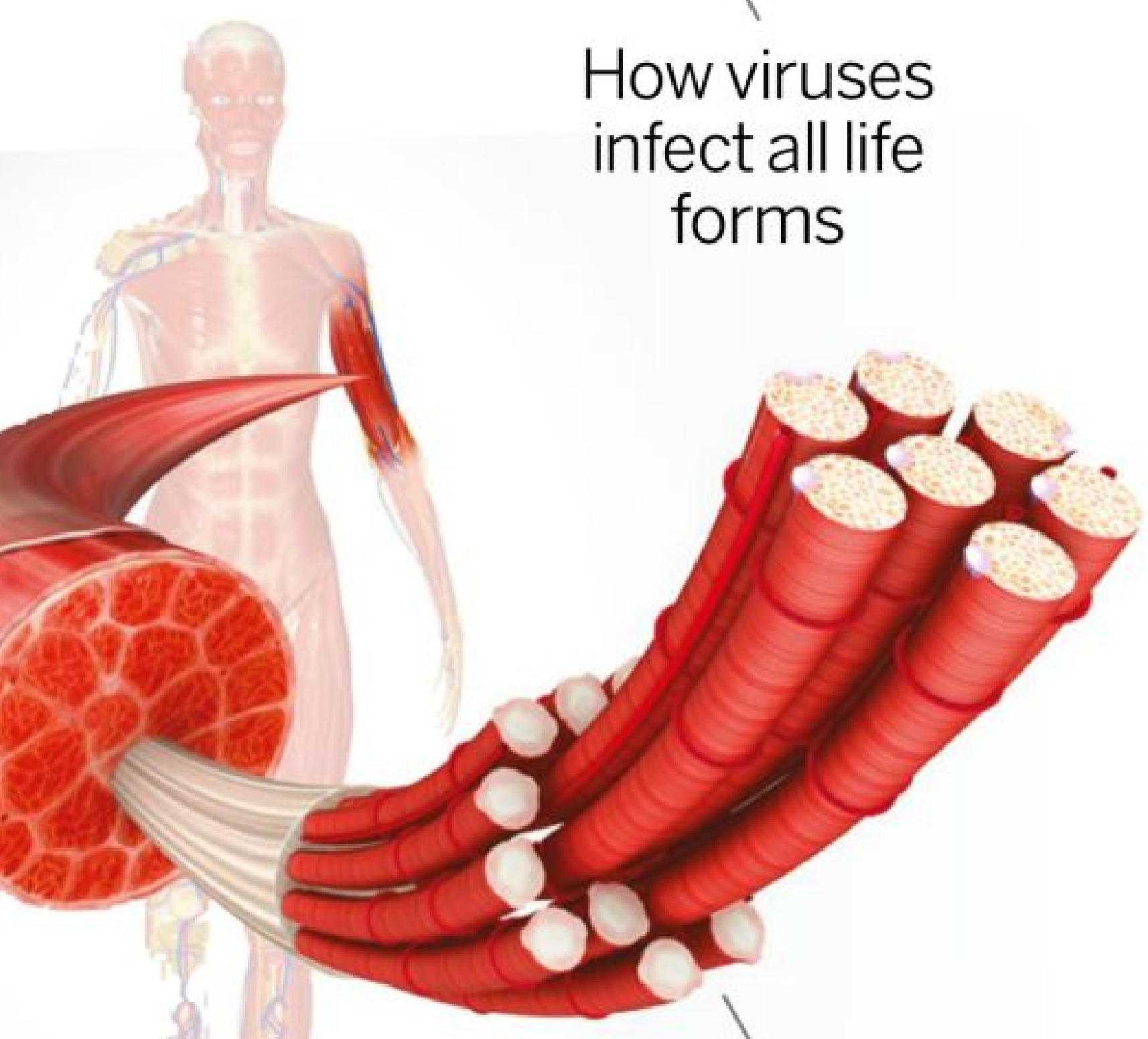

How viruses infect all life forms

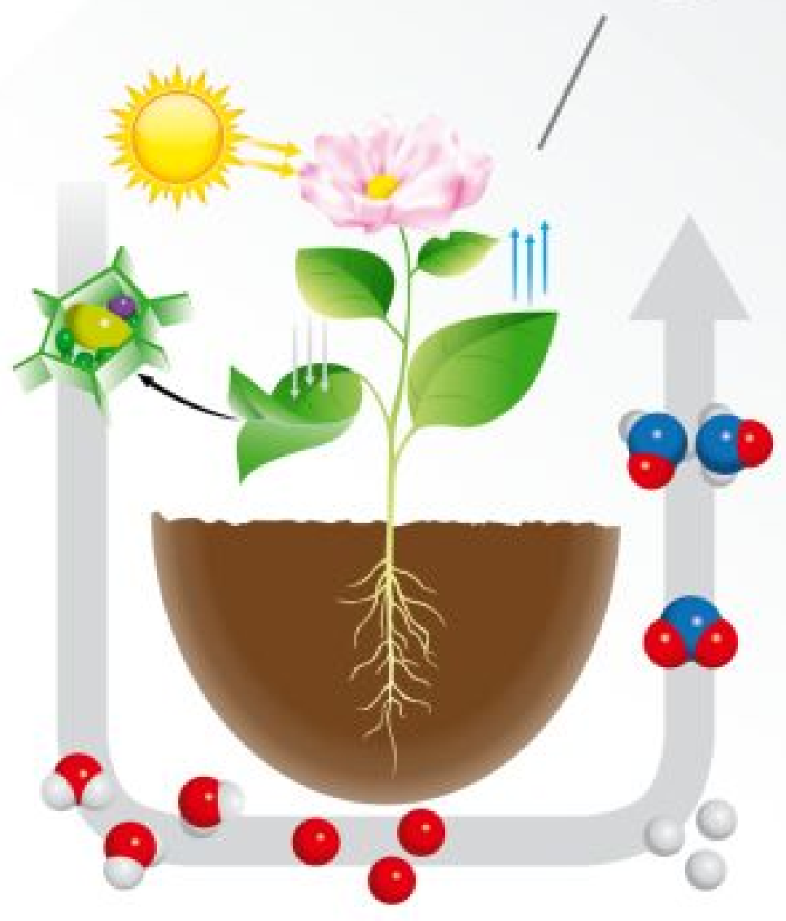
Inside the cellular universe

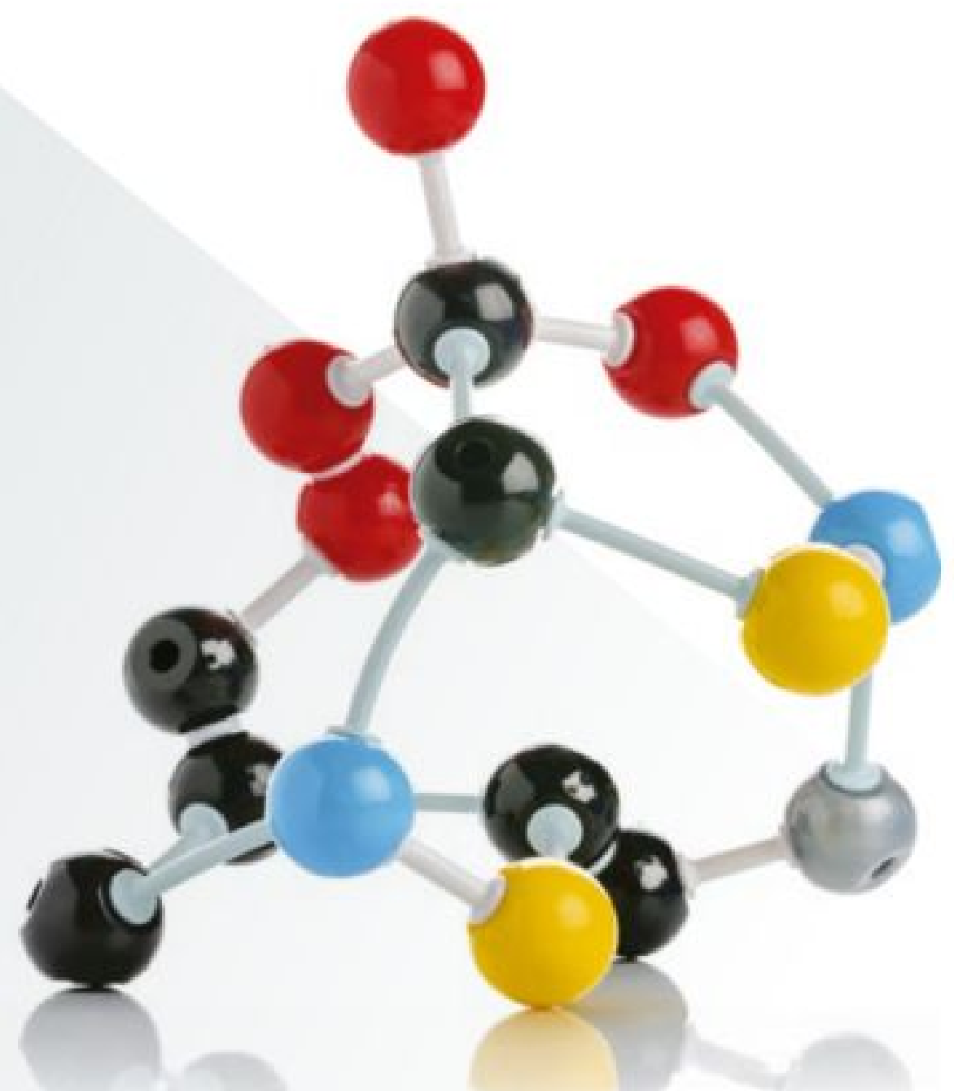
Chemical reactions that power our devices


Extraordinary antibiotics

The nerve signals that control consciousness


How muscle fibres control movement


Maintaining Earth's energy


Bonds that hold everything together

Digital Edition

FUTURE

SECOND EDITION

Welcome to
HOW IT WORKS
BOOK OF
AMAZING SCIENCE

The world of science is one that has intrigued and captivated the minds of people throughout history and all over the globe. In the How it Works Book of Amazing Science, you will discover the ways in which we plan to cure cancer, the deadliest substances known to humankind and how quantum power will propel our technology far into the future. You'll also learn how to improve your everyday life with chemistry life hacks, what happens to your body when it is put under pressure, how we make music and so much more. The beautiful thing about the different scientific disciplines is that they encourage us to question and seek out the truth about how and why everything in our world (and beyond) is as it is. Science is the ultimate pursuit of knowledge, so with that in mind, read on to learn interesting new facts and open the doors in your mind that you didn't even know were there. Enjoy!

FUTURE

BOOK OF

AMAZING SCIENCE

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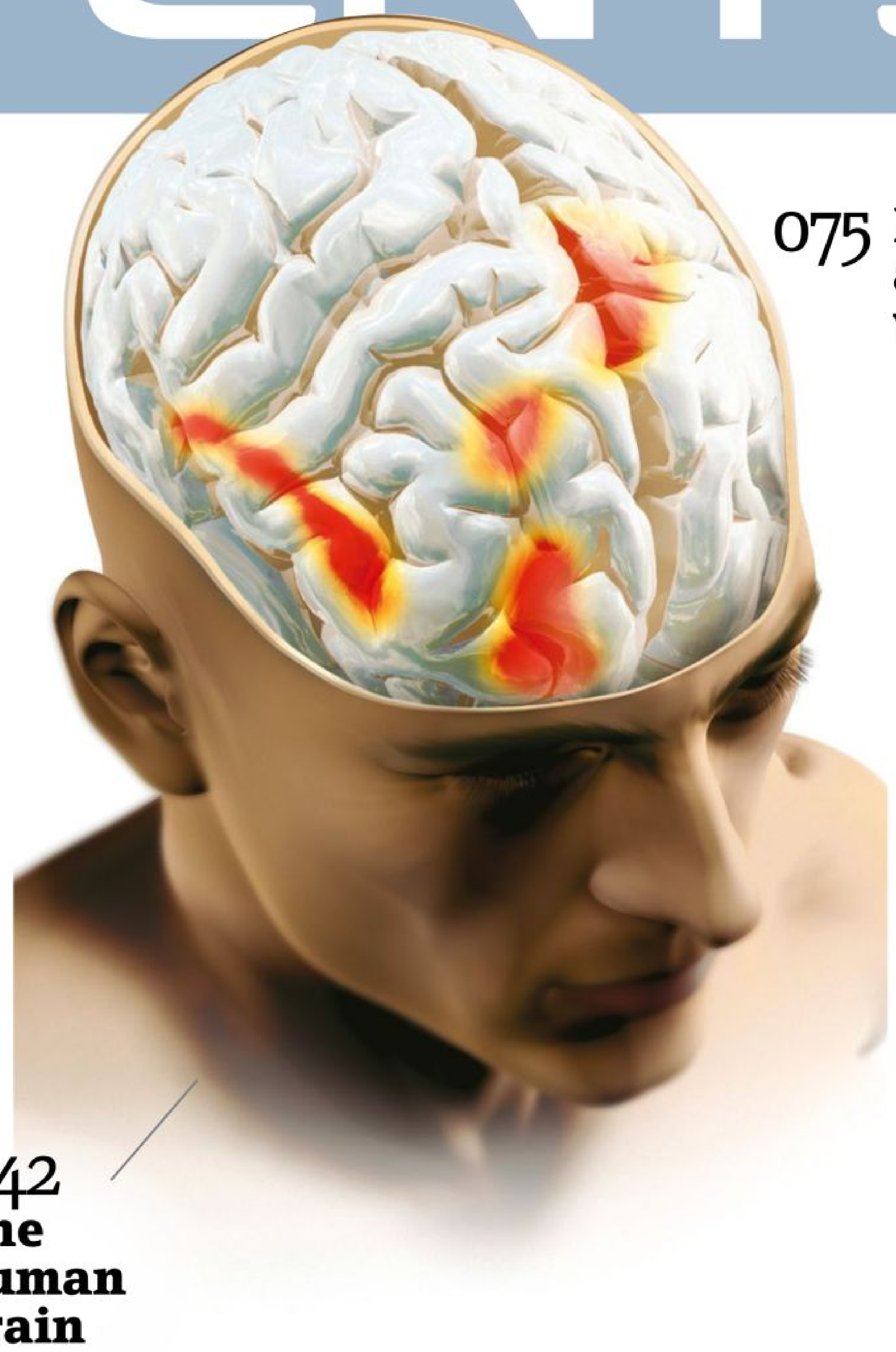
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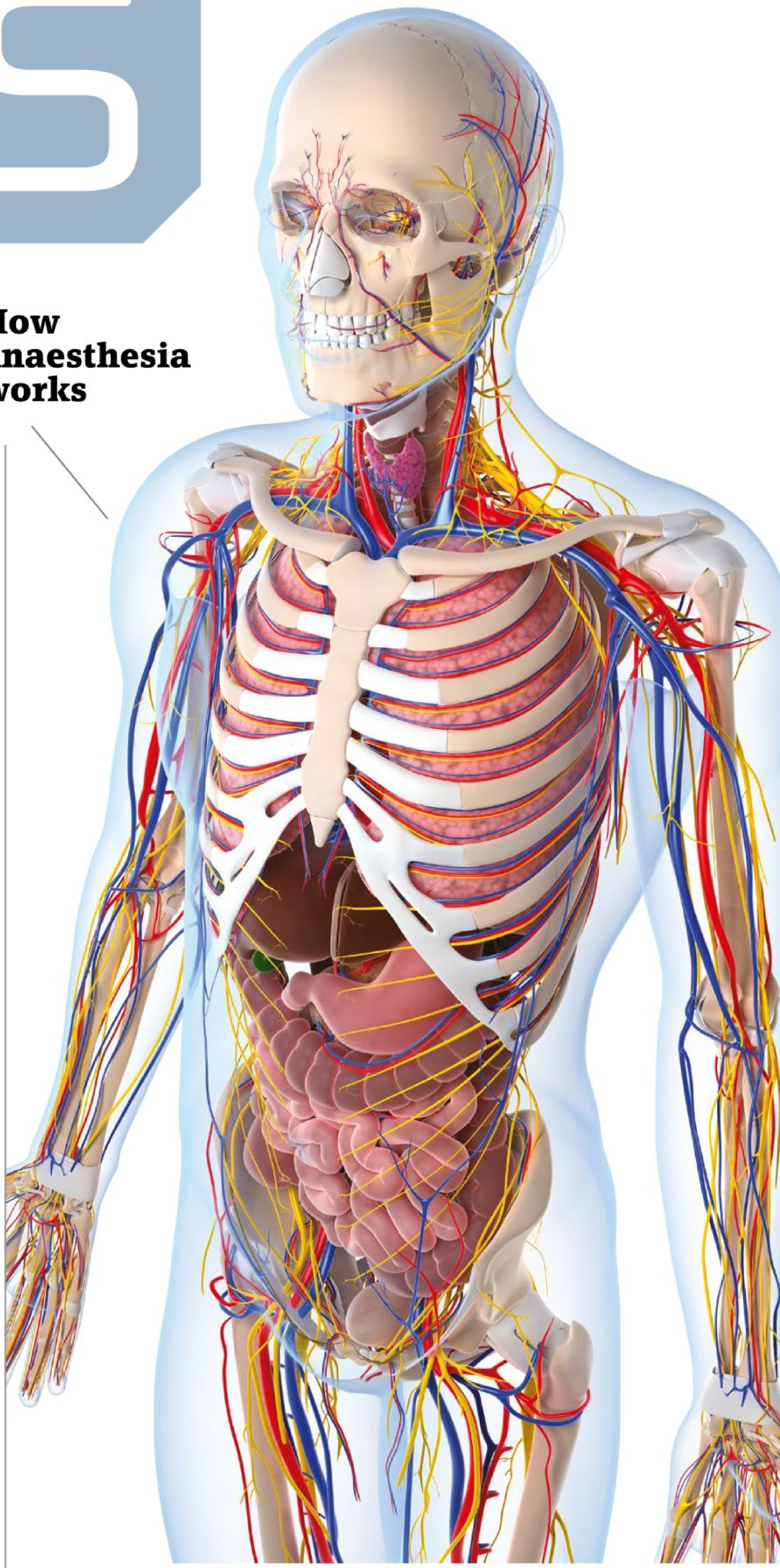
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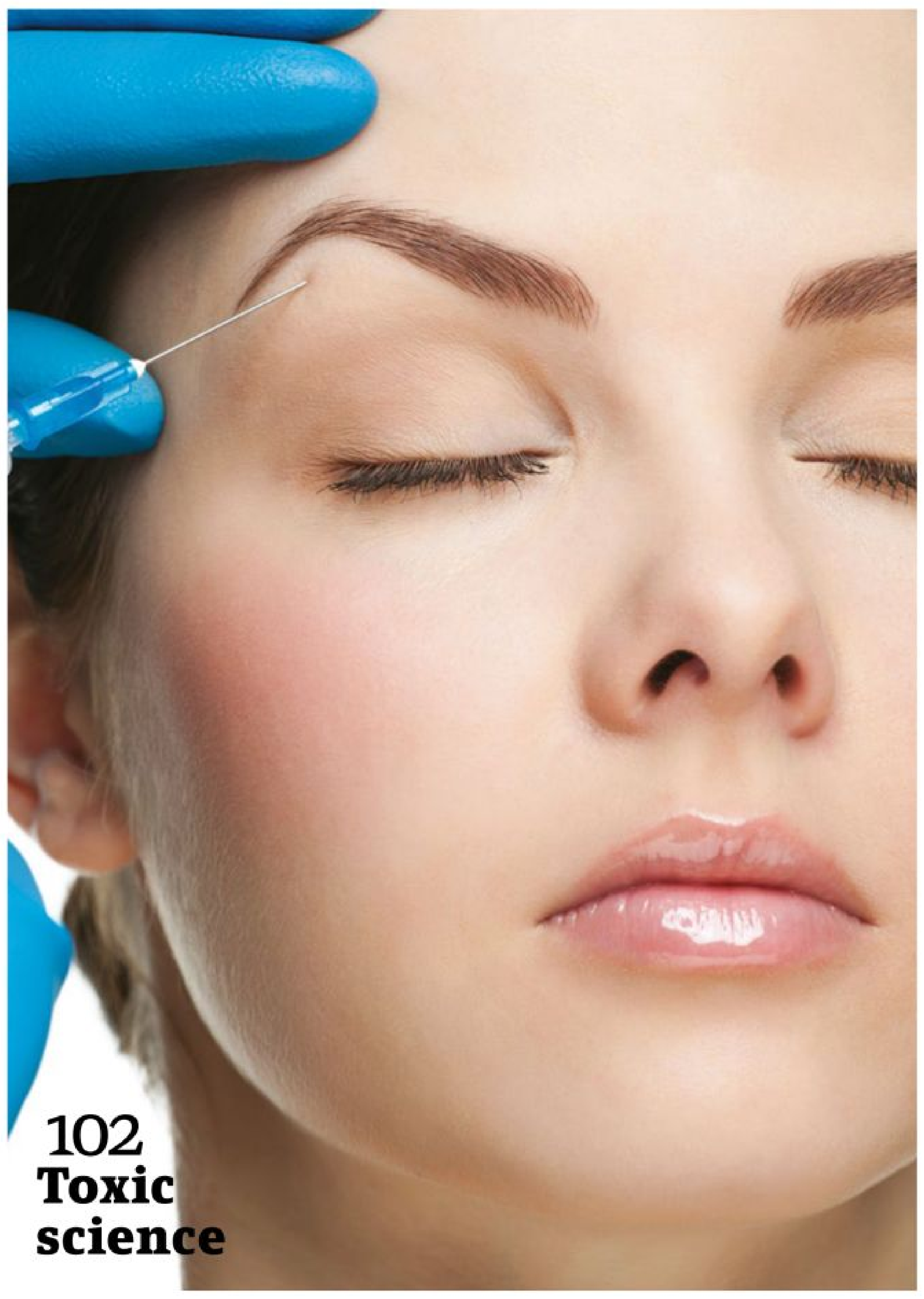

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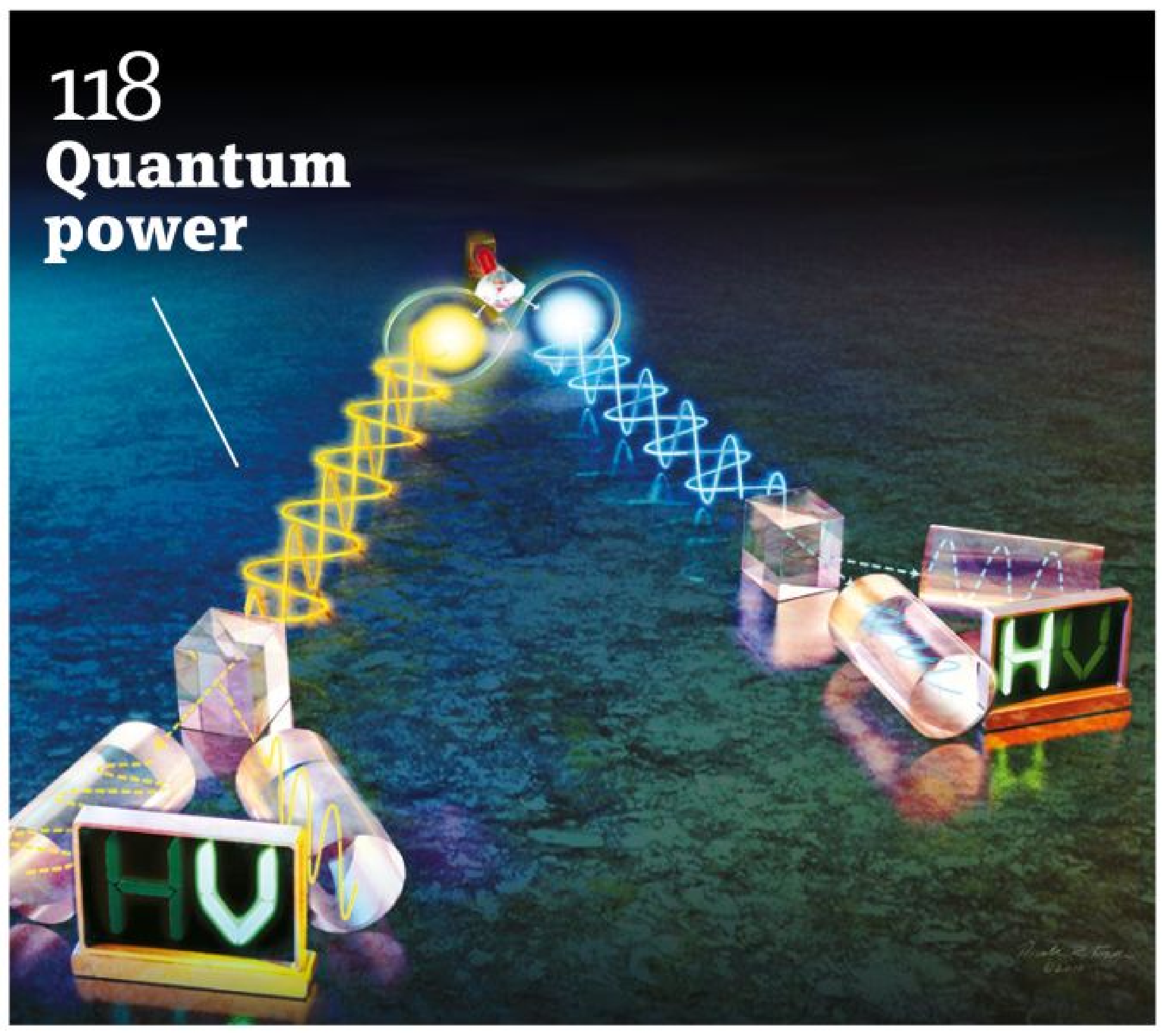

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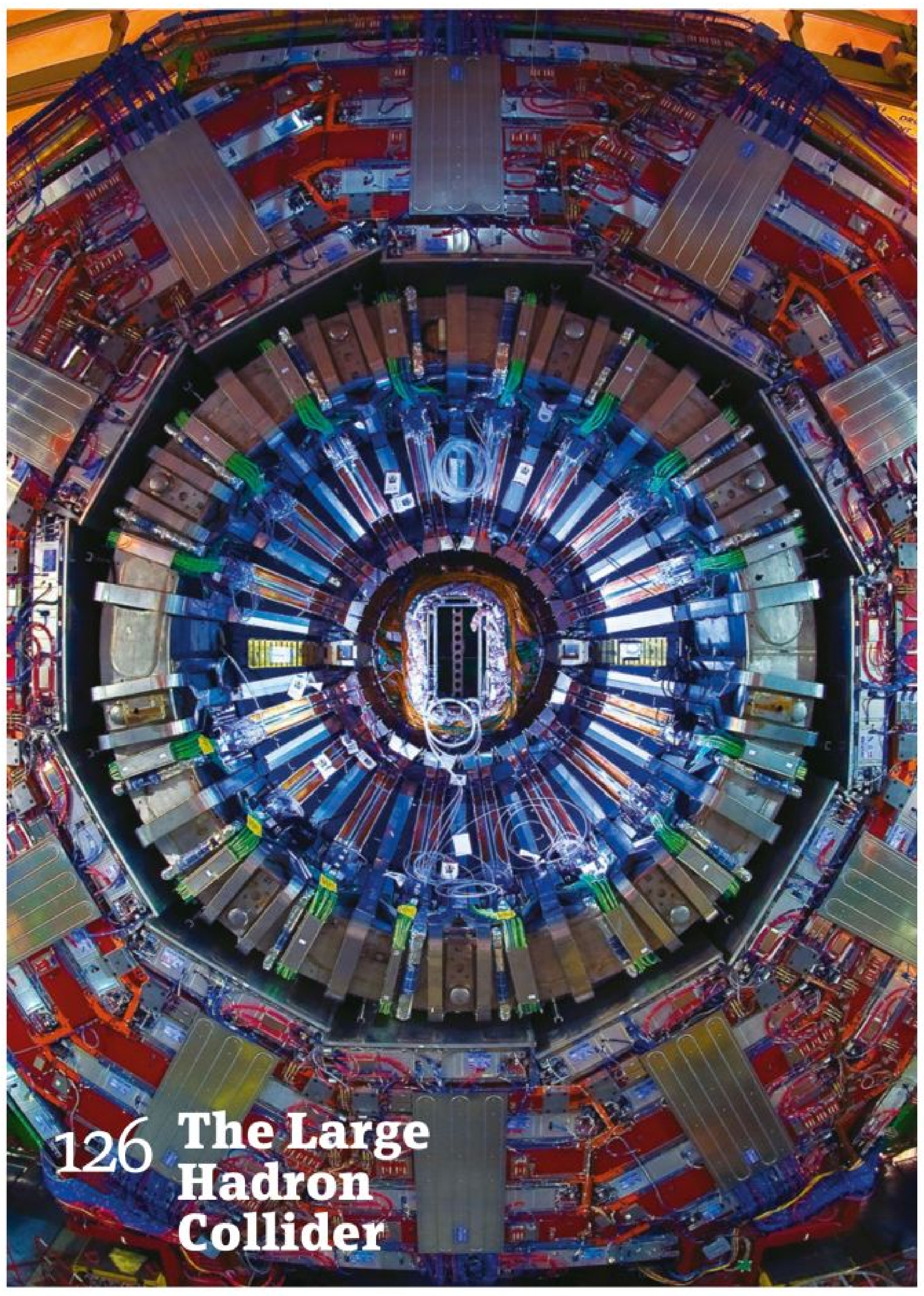

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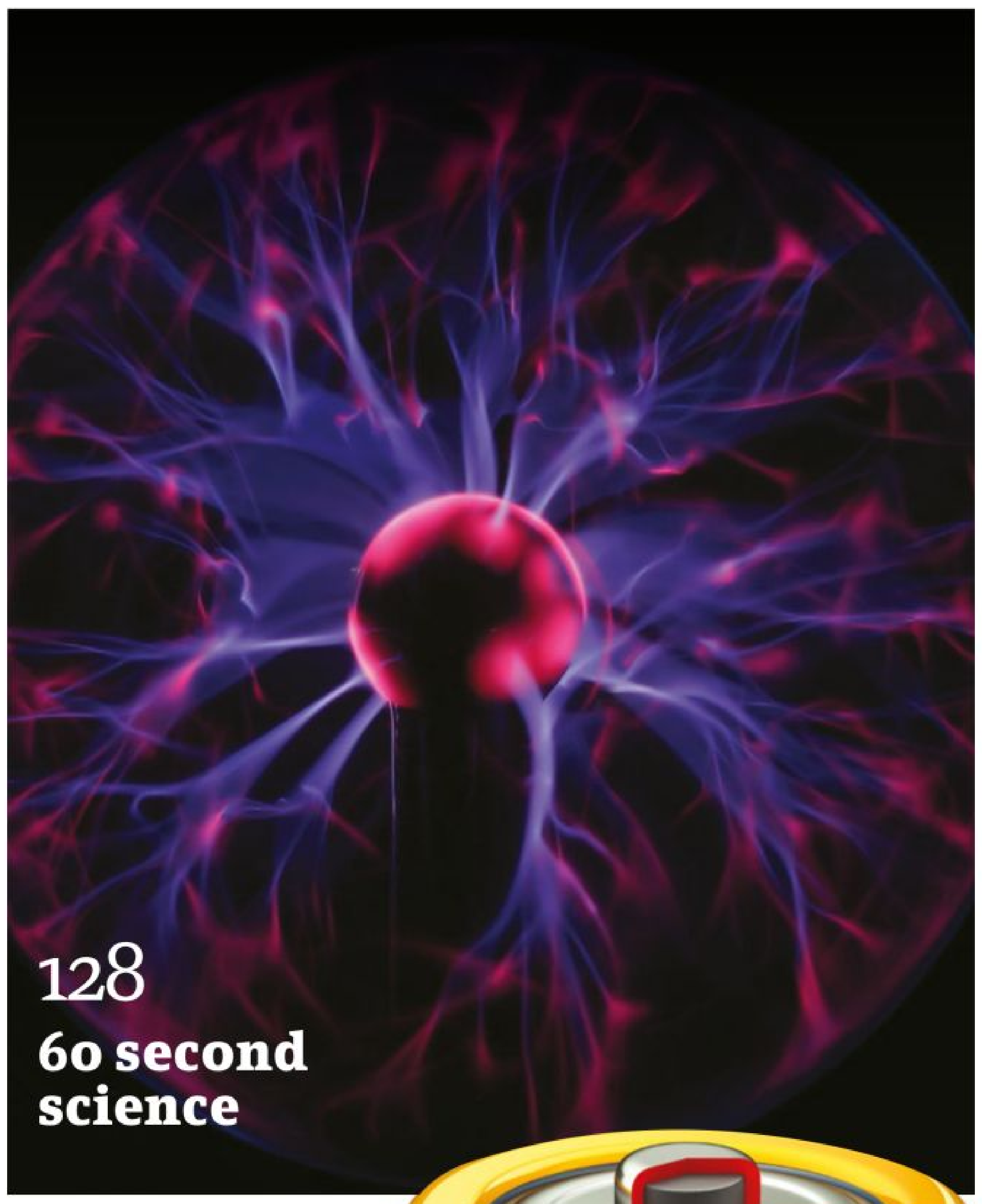

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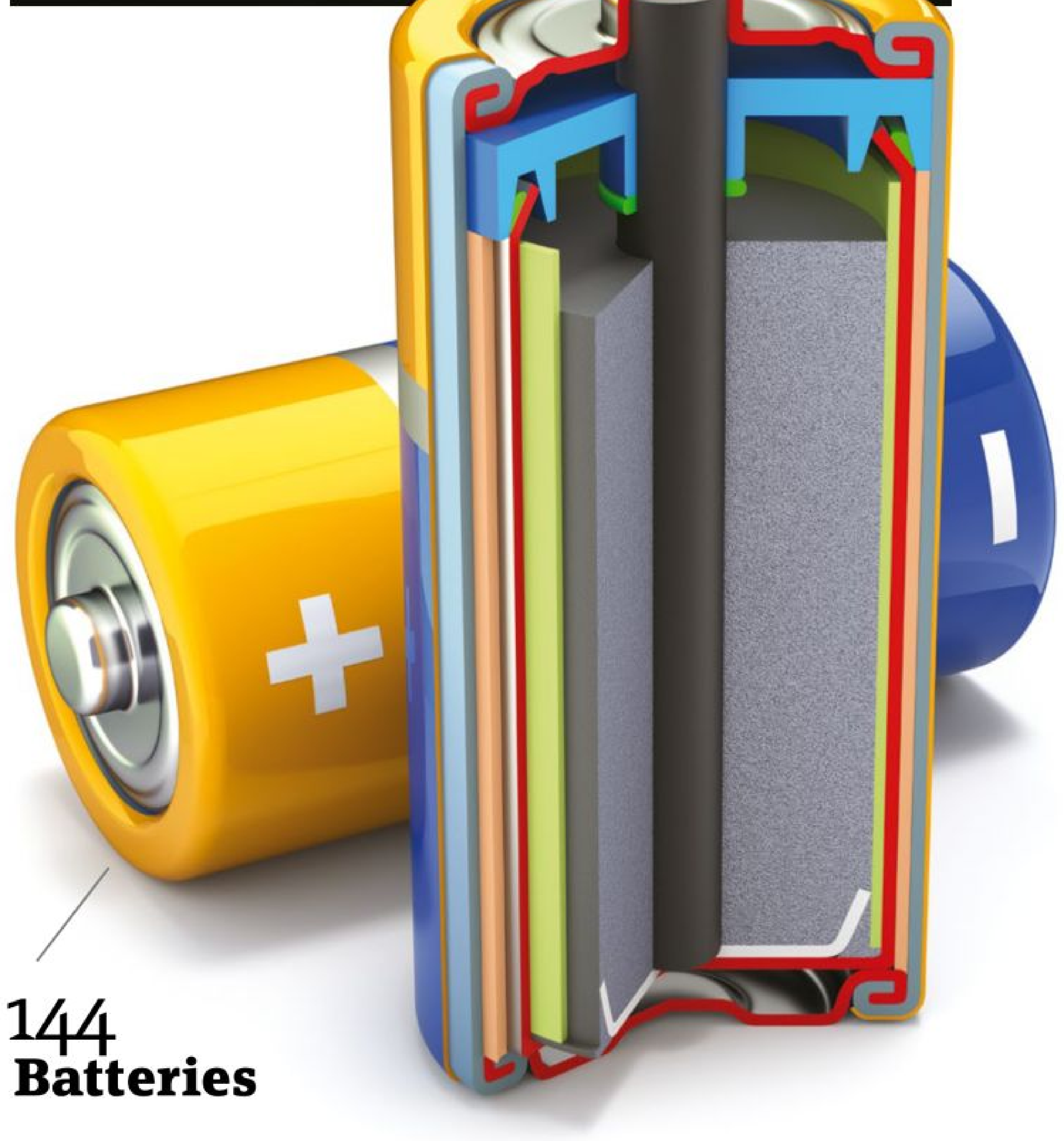

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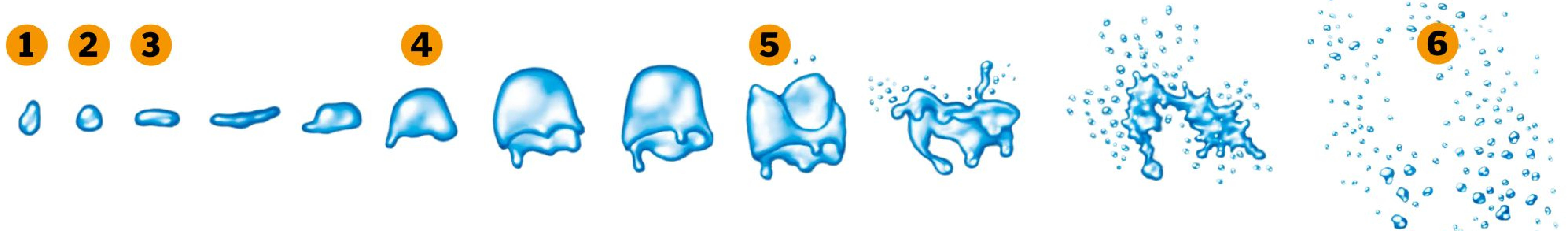
50 SCIENCE MYTHS BUSTED

Do bumblebees really defy the laws of physics? And will vitamin C actually protect you from the common cold? Discover the truth behind 50 of the world's most common myths

Rain is teardrop-shaped

01 Raindrops are often drawn with a pointed top and rounded bottom, but these simplified pictures are not even close to the truth. Raindrops form high up in the atmosphere when water clings to tiny particles of dust, and as the molecules gather together they form temporary bonds that pull the shape into a sphere. As the raindrops fall through the air, they collide with gas molecules and become distorted, widening and flattening out across the bottom. The top half forms a dome as surface tension struggles to keep the droplet together, but for raindrops over four millimetres (0.16 inches) in diameter, the weak bonds are not strong enough to hold the water together, so the droplets break apart.



1 Spherical drop Raindrops naturally form into spheres because it is the shape with the smallest surface area.

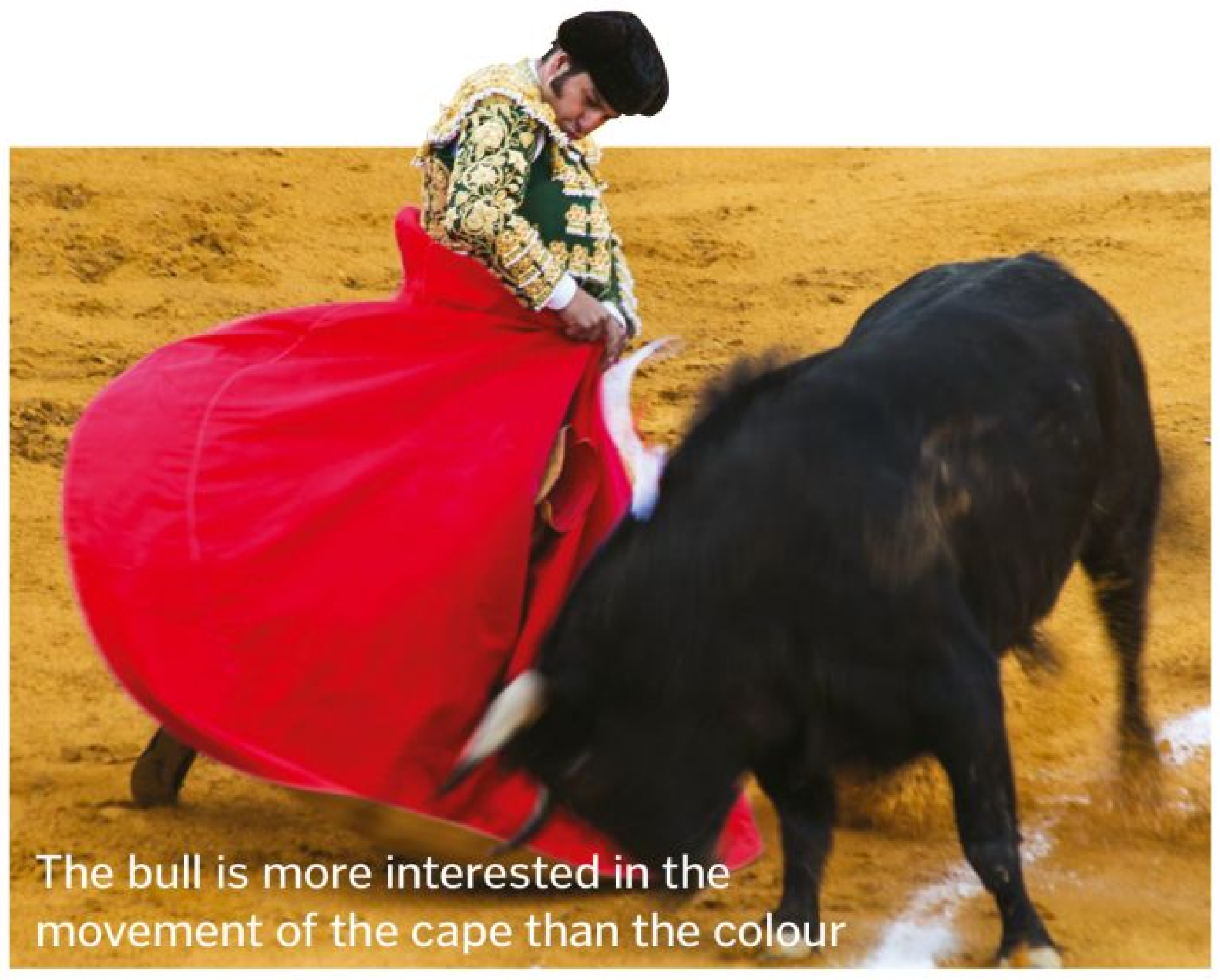
2 Surface tension Water molecules cling to one another with weak hydrogen bonds, creating surface tension.

3 Hamburger-shaped As the drops fall toward the ground, they collide with the air and the pressure flattens out the bottom edge.

4 Parachutes The largest raindrops are unable to hold themselves together and as they drop they start to distort into a parachute shape.

5 Breaking apart Raindrops over 4mm (0.16in) in diameter break up as they fall.

6 Smaller droplets The smallest droplets remain spherical as they tumble toward the ground.



The bull is more interested in the movement of the cape than the colour

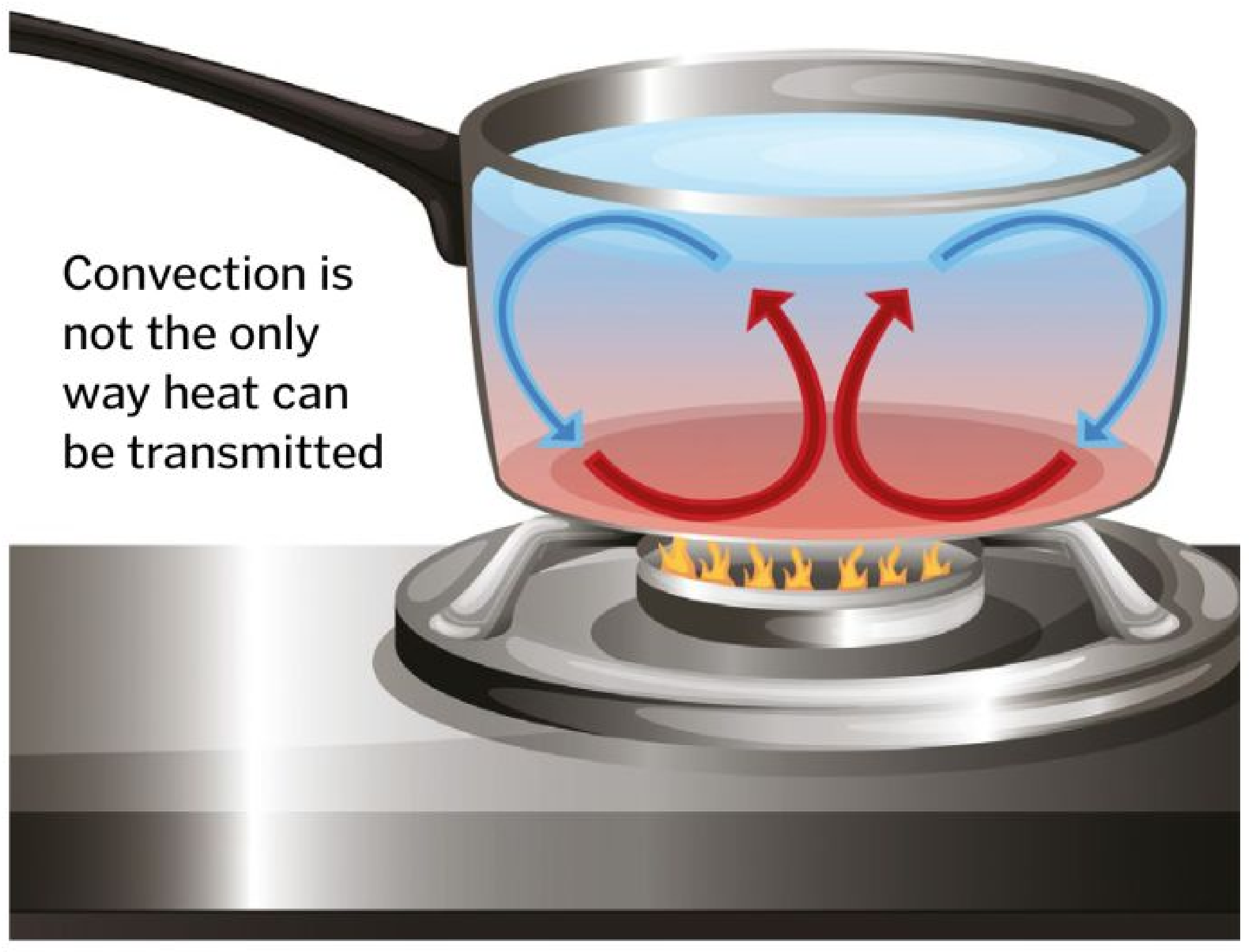
The colour red makes bulls angry

02 Bullfighters are famous for their red capes, but the idea that the colour is a trigger to anger the animals is a myth. While we can see light in red, green and blue wavelengths, bulls, like most other mammals, only have two-coloured vision. They are effectively red-green colour blind, and are more interested in the movement of the cape than its colour.

Cockroaches can withstand radiation because their cells divide less often than our own

Cockroaches can survive a nuclear apocalypse

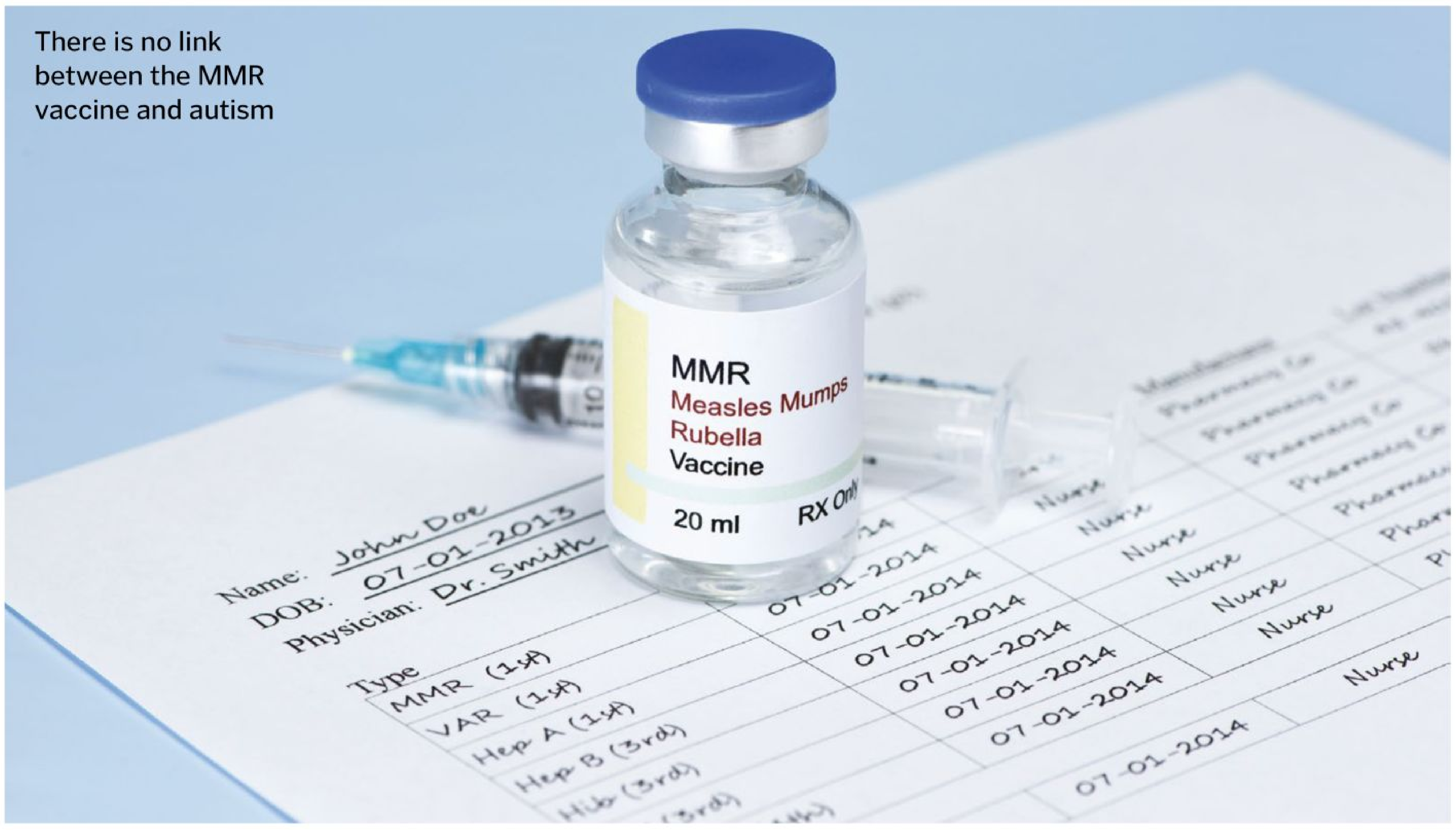
03 Cockroaches are capable of withstanding much higher levels of radiation than humans and are often listed amongst the animals that will inherit the Earth in the event of a nuclear apocalypse. However, while adult roaches can survive radiation levels equivalent to those released by the Hiroshima nuclear bomb, their fertility is adversely affected by much lower levels of radiation.



Convection is not the only way heat can be transmitted

Heat rises

04 This simple myth persists because for many situations it appears to be true. As liquids and gases gain energy, they heat up and expand, which lowers the density compared to cold fluid, causing the hot region to rise. However, heat also transferred by infrared radiation and conduction, both of which can occur in any direction.



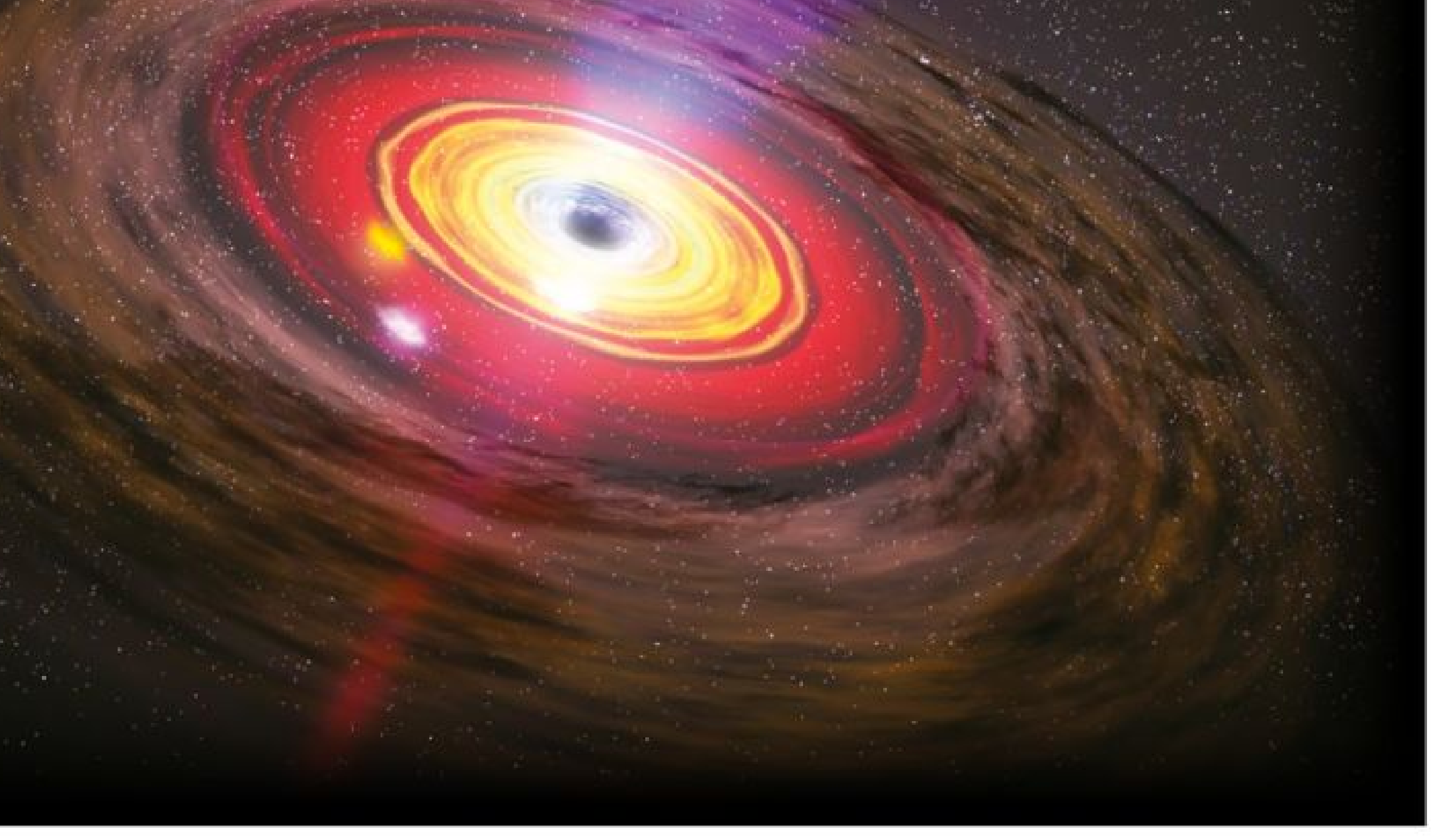
There is no link between the MMR vaccine and autism

Vaccinations cause autism

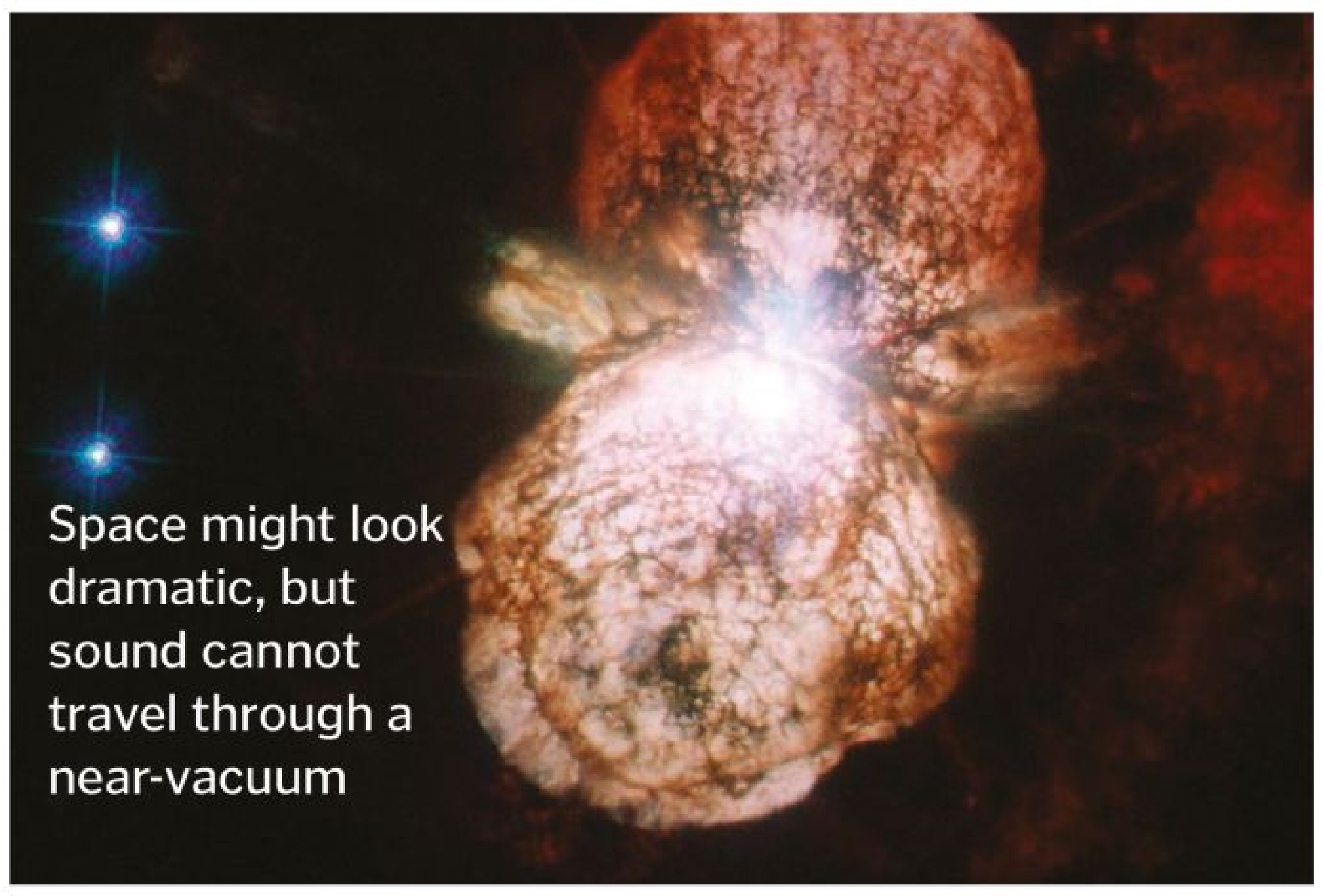
05 This is one of the most dangerous science myths of all and was born out of a combination of fraudulent research and irresponsible media hype. The 'evidence' supporting a link between the MMR vaccine and autism was misreported, and the results were distorted by the media, which spread the idea there was a link between autism and immunisation. Repeated investigations have confirmed the original data was false, but the myth has caused lasting damage and the rate of measles infections in the UK has risen as a result.

The Large Hadron Collider could create a black hole and destroy the Earth

06 With the upgraded LHC being switched on again at CERN in 2015, the apocalyptic myths about black holes are resurfacing, as people are wondering whether two protons slamming into one another at high speed could produce a black hole. Some physicists think that is possible, but the resulting black hole would be microscopic and would do no damage to the Earth.



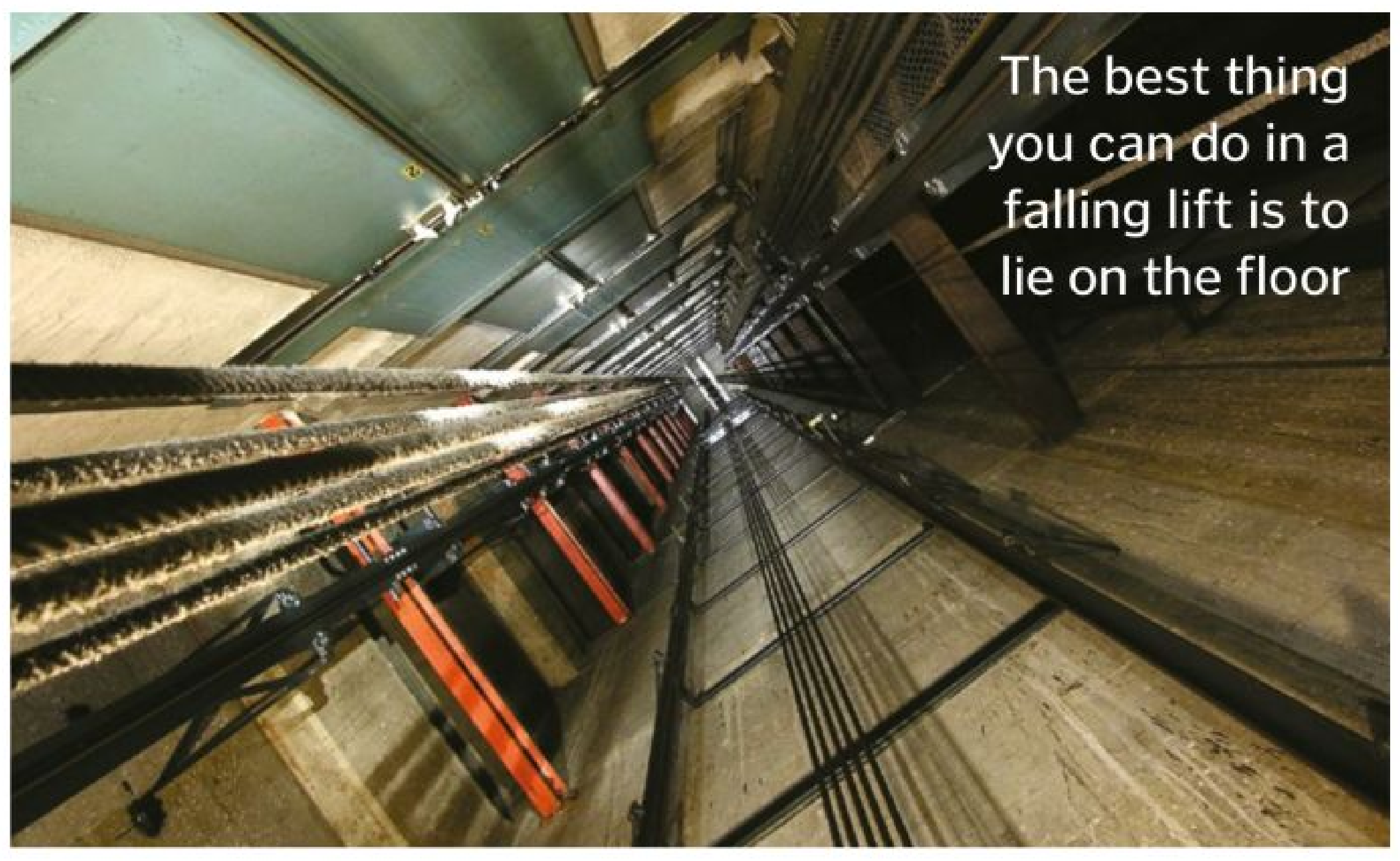
The LHC is not capable of creating a black hole that could destroy the Earth



Space might look dramatic, but sound cannot travel through a near-vacuum

A firefight in space would be loud, just like in the movies

07 Sound propagates when vibrations are transferred from one particle to the next, but in outer space there are so few particles, spread so far apart, that the vibrations cannot travel. So despite the popular Hollywood scenes depicting loud explosions, in space nothing makes a sound.



The best thing you can do in a falling lift is to lie on the floor

In a falling lift, you should jump before you hit the floor

08 People often wonder whether they could jump just before a falling lift hits the floor, avoiding the impact of the crash, but unfortunately this tactic will not work. You are falling at the same speed as the lift, and as you push away from the floor in the opposite direction you are only counteracting a fraction of that downward acceleration.

© Dreamstime; Thinkstock; NASA

Antibiotics can treat flu

09 Antibiotics are bacteria-busting drugs, so they are no use against flu or the common cold, both of which are caused by viruses. Antibiotics work by blocking the chemical processes bacteria use to survive and reproduce, but viruses hijack our own cells to replicate and are unaffected by these drugs.

Drawing on skin causes ink poisoning

10 Inks used to be made from dangerous chemicals, but today most pens have water or alcohol-based inks and are nontoxic. It takes a large amount of ink to cause poisoning and the most common routes of ingestion are either swallowing or inhaling, not drawing.

Bats are blind

11 Bats are well known for using echolocation to find their way through the darkness, but their mastery of hearing does not mean they are blind. All bats have eyes and can see. Some of the larger fruit-eating species have eyesight even better than our own.

Go out with wet hair and you'll catch a cold

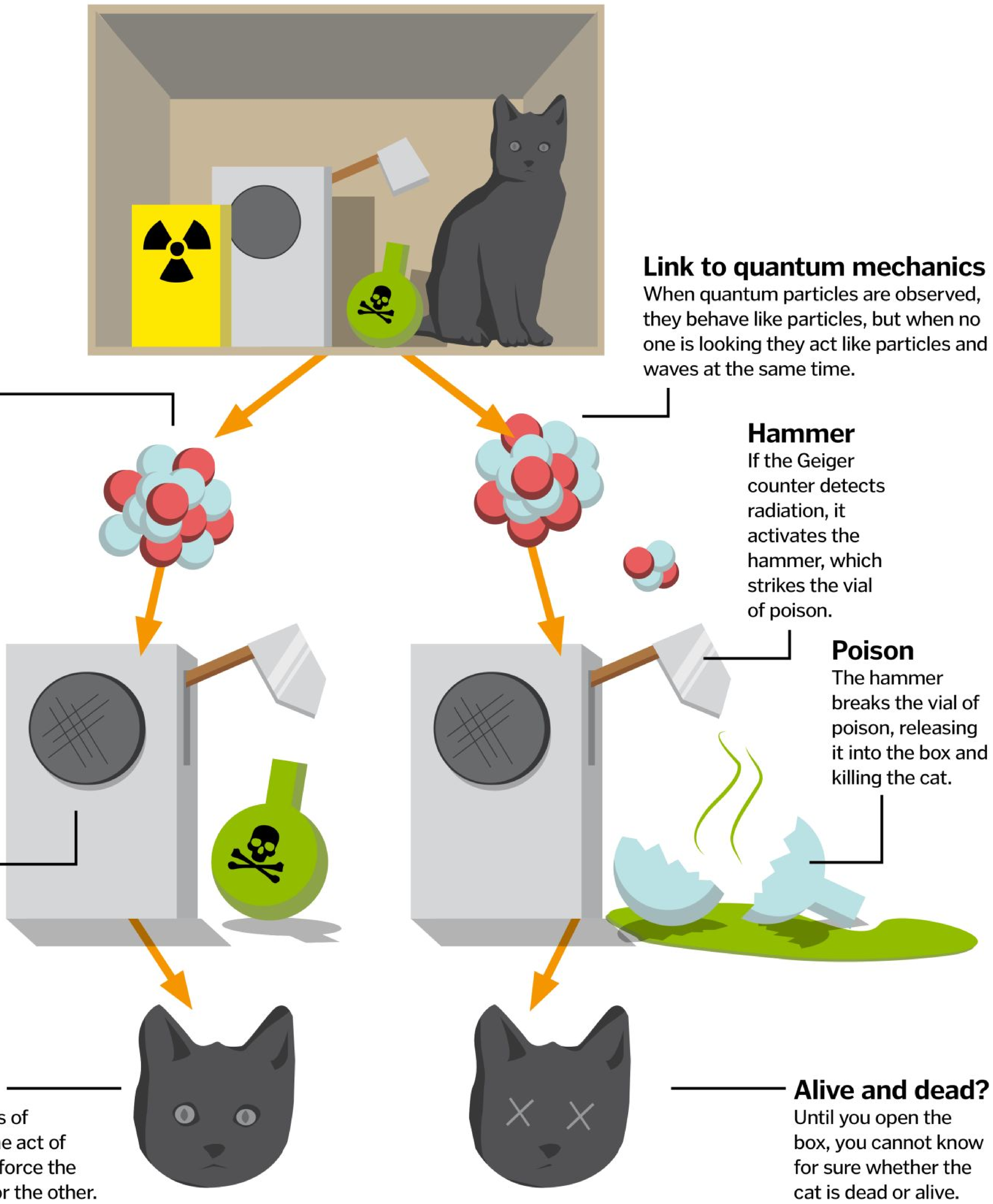
12 There is nothing special about wet hair that will increase your chances of catching the cold virus, but there is actually a grain of truth behind this myth. Getting chilly can increase your likelihood of developing the symptoms of a cold; possibly by decreasing the blood flow to your nose, thus enabling the virus to replicate.

White spots signal calcium deficiency

13 The white marks that appear on fingernails are known as leukonychia, and many people believe they are the result of mineral deficiency. However, the real cause is most often damage to the nails from knocks, bumps and even wearing false nails, all of which can cause abnormal marks to form at the nail plate.

Schrödinger's cat is both dead and alive

14 In 1935, Erwin Schrödinger devised a thought experiment involving a cat locked in a steel box with a Geiger counter, a radioactive substance, a vial of poison and a hammer. If radioactive decay triggers the Geiger counter, the hammer will strike the vial of poison and kill the cat. However, because radioactive decay happens at random, you cannot know whether the cat is dead or alive until you look inside the box. Does this mean that the cat is both dead and alive at the same time? Well no, despite popular belief, Schrödinger was actually trying to point out the absurdity of quantum theory with an impossible example and was not suggesting that a cat could be both dead and alive.



Link to quantum mechanics
When quantum particles are observed, they behave like particles, but when no one is looking they act like particles and waves at the same time.

Radioactive material
Unstable atoms spontaneously emit ionising radiation, but it is impossible to predict exactly when this might happen.

Hammer
If the Geiger counter detects radiation, it activates the hammer, which strikes the vial of poison.

Poison
The hammer breaks the vial of poison, releasing it into the box and killing the cat.

Geiger counter
Any radiation released within the box will be detected by the Geiger counter.

Observer effect
In parallel with the ideas of quantum mechanics, the act of opening the box would force the cat to adopt one state or the other.

Alive and dead?
Until you open the box, you cannot know for sure whether the cat is dead or alive.

Sinks drain in different directions on either side of the equator

15 It is often claimed that the spin of the Earth affects the way water drains out of the sink, and that to the north of the equator it swirls down the drain in a clockwise direction, while to the south it turns anticlockwise. While the Earth's spin does affect the rotation of hurricanes in what is known as the Coriolis effect, the amount of water in a sink is so small that Earth's spin does not affect the direction it drains, so in reality it is down to way the water is poured into the bowl and whether there are any imperfections in the surface.

The direction the water drains is not decided by the spin of the Earth

Bumblebees shouldn't be able to fly

16 The myth that bumblebee flight is impossible under the laws of physics has been traced back to the first half of the 20th century, when our understanding of flight was much more basic than it is today. According to early calculations, the wings of a bumblebee were too small to generate enough lift, however, using smoke and high-speed cameras, scientists at the University of Oxford watched bumblebees fly. They are not aerodynamic, but they do not break any laws of physics in the air.

Bumblebees don't look very aerodynamic, but their flight does not defy physics

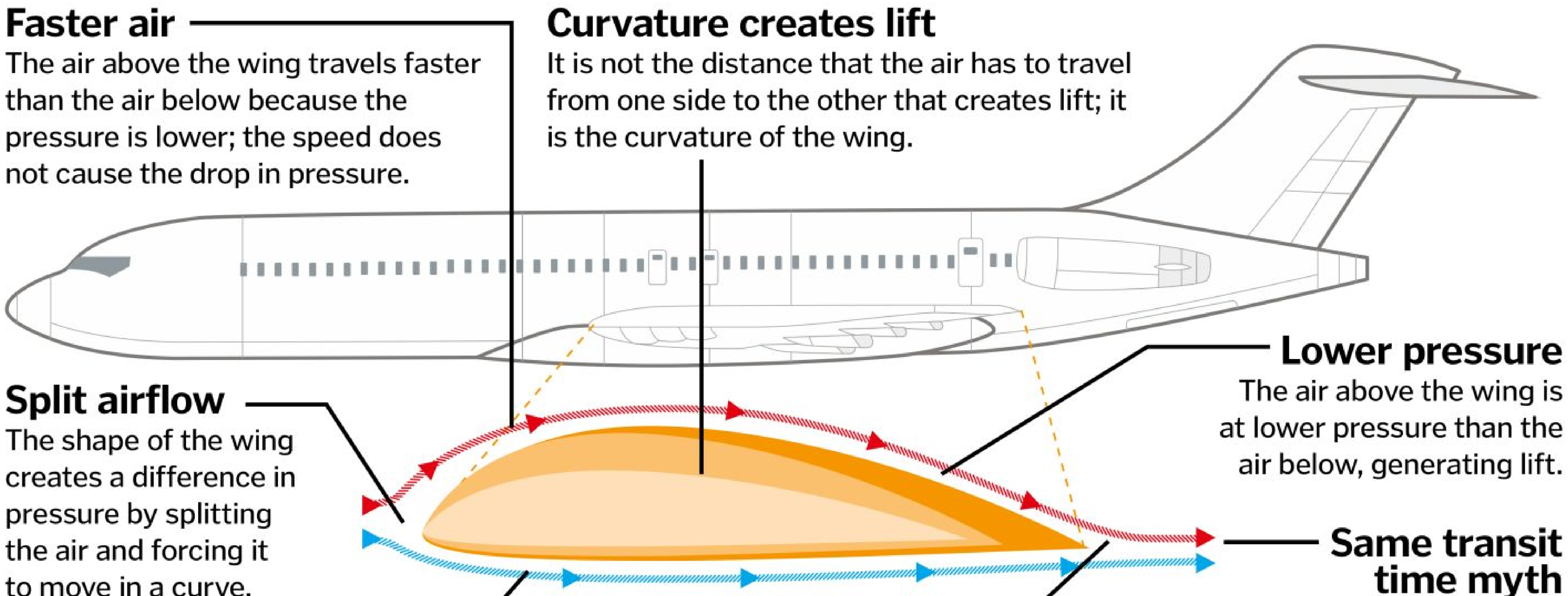
Groups of lemmings deliberately hurl themselves off cliffs

17 A film made by Walt Disney in 1958 called White Wilderness showed footage of lemmings leaping into the sea in an apparent mass suicide. However, in 1983 it was found the footage had been staged, using imported animals and tight camera angles to disguise the environment. In reality, the crew had herded the lemmings over the edge. It is true that when lemming populations get too high the animals disperse, gathering in numbers near the edges of rivers before attempting to swim across, but they do not deliberately jump to their deaths.

Lemmings are able to swim, so they jump into the water to disperse, not to die

Air takes the same amount of time to travel over and under an aircraft wing

18 One of the most famous misconceptions about aeroplane flight is that their wings are shaped so that the upper surface is longer than the lower surface, and that this forces the air moving over the top to move faster than the air underneath, which in turn creates a pressure difference and generates lift. However, as NASA points out; if this were true, how could planes fly upside down? If you take aerofoil with upper and lower surfaces of equal length, you generate lift even though the air has to travel the same distance.



Faster air
The air above the wing travels faster than the air below because the pressure is lower; the speed does not cause the drop in pressure.

Curvature creates lift
It is not the distance that the air has to travel from one side to the other that creates lift; it is the curvature of the wing.

Lower pressure
The air above the wing is at lower pressure than the air below, generating lift.

Split airflow
The shape of the wing creates a difference in pressure by splitting the air and forcing it to move in a curve.

Same transit time myth
The air moving over the surface of the wing actually reaches the end before the air travelling underneath.

Shaping the airflow
The curved wing alters the path of the air, creating pressure differences.

Bad physics
There is no physical law that states that the air on the top and bottom should take the same time to travel over the wing.

Bananas grow on trees, and those trees can walk

19 Banana plants might look like trees, but they are actually herbs with 'trunks' made from tightly wrapped leaves. The bananas themselves are classified as berries. Beneath the ground the plants have a network of sideways-branching roots known as rhizomes, which spread out laterally and creep away under the soil. From these hidden roots, new leaves can spring up far from the original stem, making it appear as though the banana plant has moved.

Special 'superfoods' will do wonders for your health

20 Foods like blueberries and kale top the charts for their claimed health benefits, but the whole concept of 'superfoods' is a fabrication. There is no legal definition of a superfood, and the claimed health benefits are often based on experiments performed in test tubes with abnormally high amounts of the beneficial chemicals. These kinds of marketing myths can be dangerous, and not only is there no evidence to support many superfood claims; some supplements may even be harmful to human health.

The rust on a dirty nail causes tetanus

21 It is well known that if you are cut with rusty metal, you should check that your vaccinations are up to date, but it is not the rust itself that causes tetanus. Tetanus is the result of a bacterial infection called Clostridium tetani, which exists as spores in the soil, and can survive for decades at a time. If metal is rusty, it means it has probably been left outside for an extended period, making it more likely to have come into contact with the bacteria.

Swimming after eating gives you cramp

22 It is often claimed that entering the water on a full stomach can lead to deadly cramps, but if this were true, then why would endurance swimmers risk eating during a race? The pressure of a full stomach can cause a stitch, but in the event of this happening in the water, it is very unlikely the pain would be so bad that it would result in drowning.

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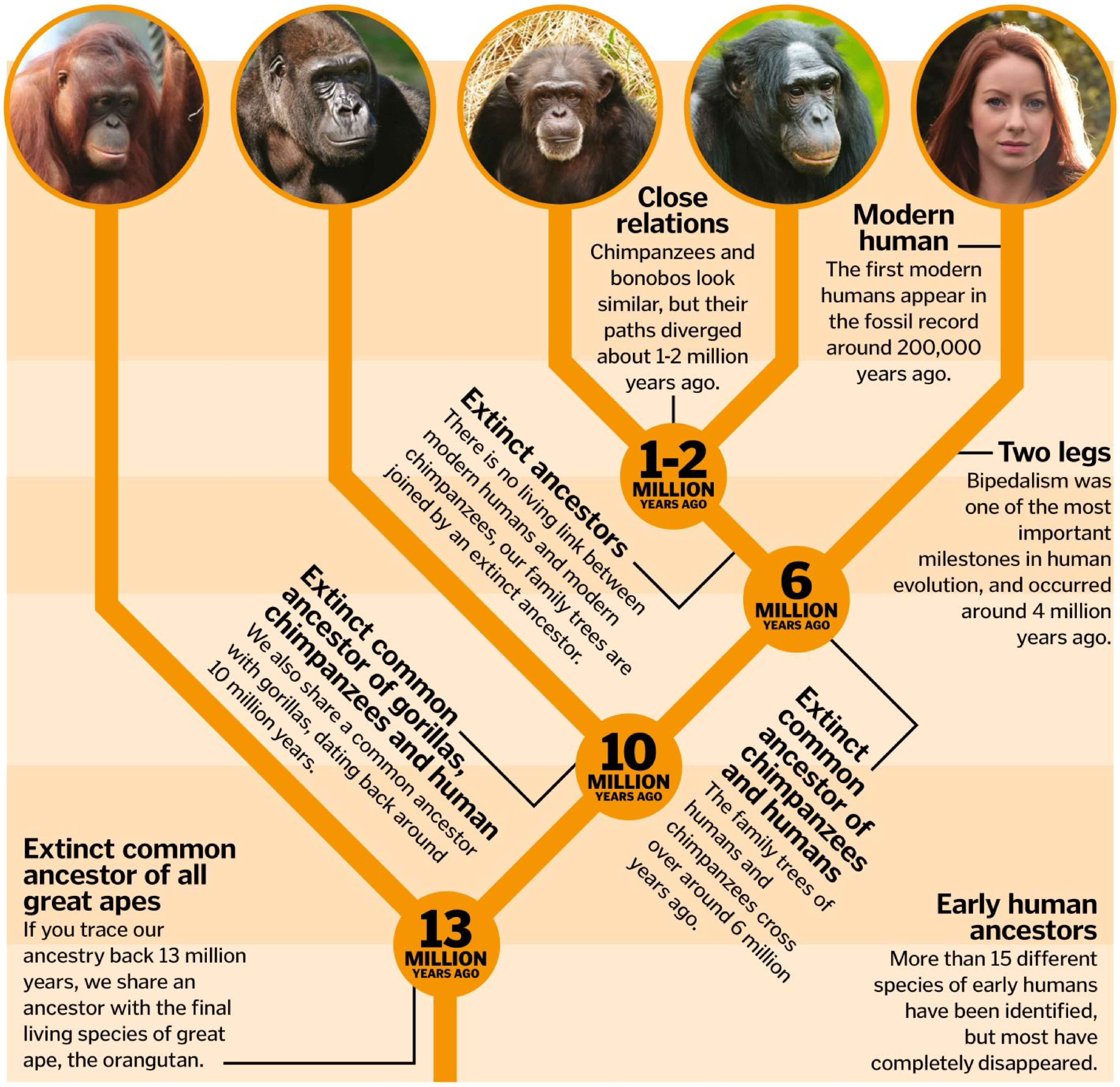
Humans evolved from chimpanzees

23 One of the most common misinterpretations of the theory of evolution is the idea that we are descended from chimpanzees. We are closely related; we are both primates and share 98.8 per cent of the same DNA, but the African apes are our cousins, not our ancestors. If you traced the family trees of chimpanzees and humans, the two would cross over at a point around 6 million years ago. This common ancestor was neither a human nor a chimpanzee, and the descendants of that now-extinct species went down different evolutionary paths, leading to the modern species we see today.



Close relations
Chimpanzees and bonobos look similar, but their paths diverged about 1-2 million years ago.

Modern human
The first modern humans appear in the fossil record around 200,000 years ago.

Two legs
Bipedalism was one of the most important milestones in human evolution, and occurred around 4 million years ago.

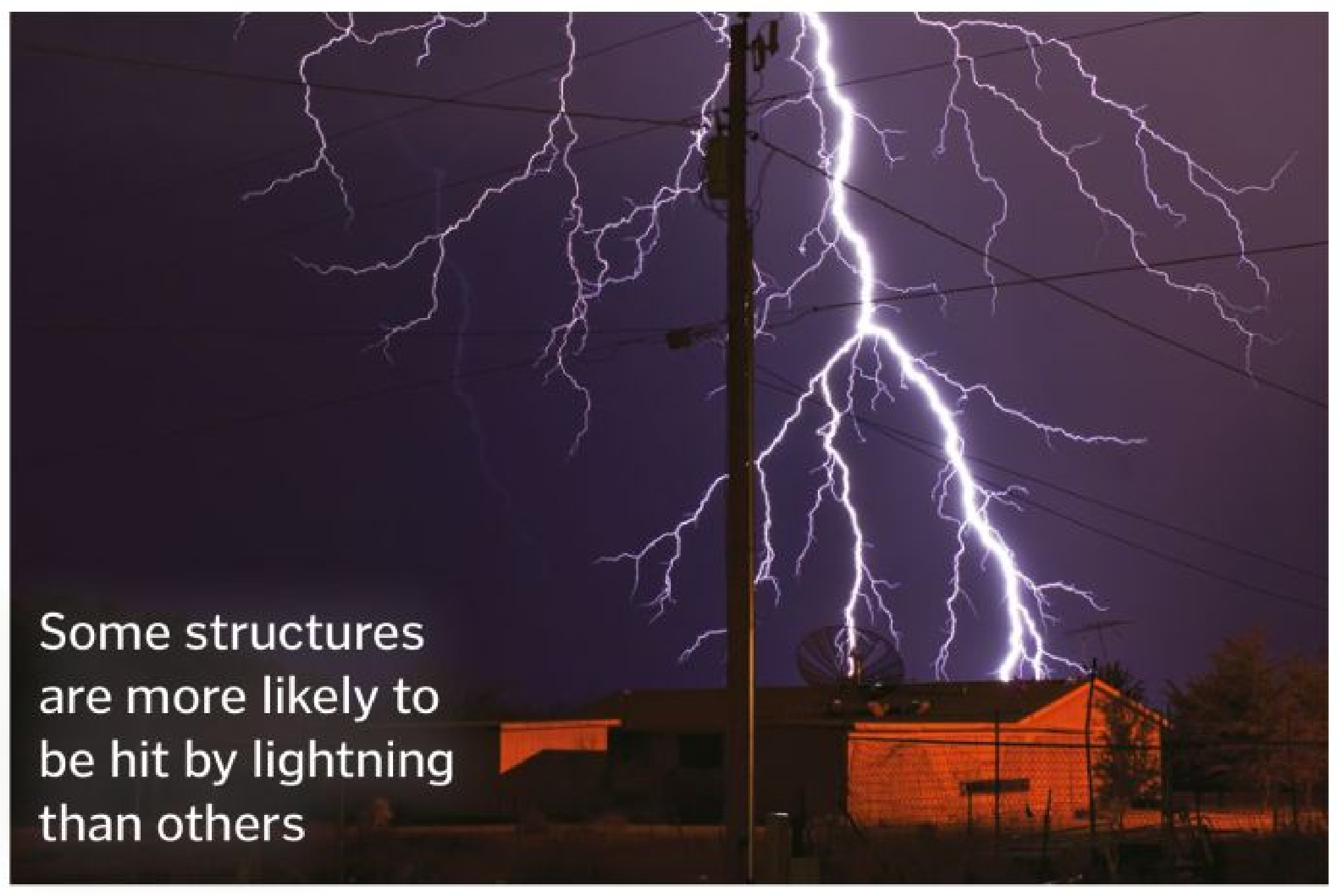
Extinct ancestors
There is no living link between modern humans and modern chimpanzees, our family trees are joined by an extinct ancestor.

Extinct common ancestor of gorillas, chimpanzees and human
We also share a common ancestor with gorillas, dating back around 10 million years.

Extinct common ancestor of chimpanzees and humans
The family trees of humans and chimpanzees cross over around 6 million years ago.

Extinct common ancestor of all great apes
If you trace our ancestry back 13 million years, we share an ancestor with the final living species of great ape, the orangutan.

Early human ancestors
More than 15 different species of early humans have been identified, but most have completely disappeared.



Some structures are more likely to be hit by lightning than others

Lightning doesn't strike in the same place twice

24 If the Earth were an even sheet, with equal distribution of elements, lightning would have the same probability of striking each area, so the chance of two strikes in the same place would be low. However, our planet is lumpy, and variations like the height of a building, the moisture in the soil and even the positioning of leaves can make lightning more likely to strike in one place repeatedly.

The smell of a human will not prevent birds from returning to their nests

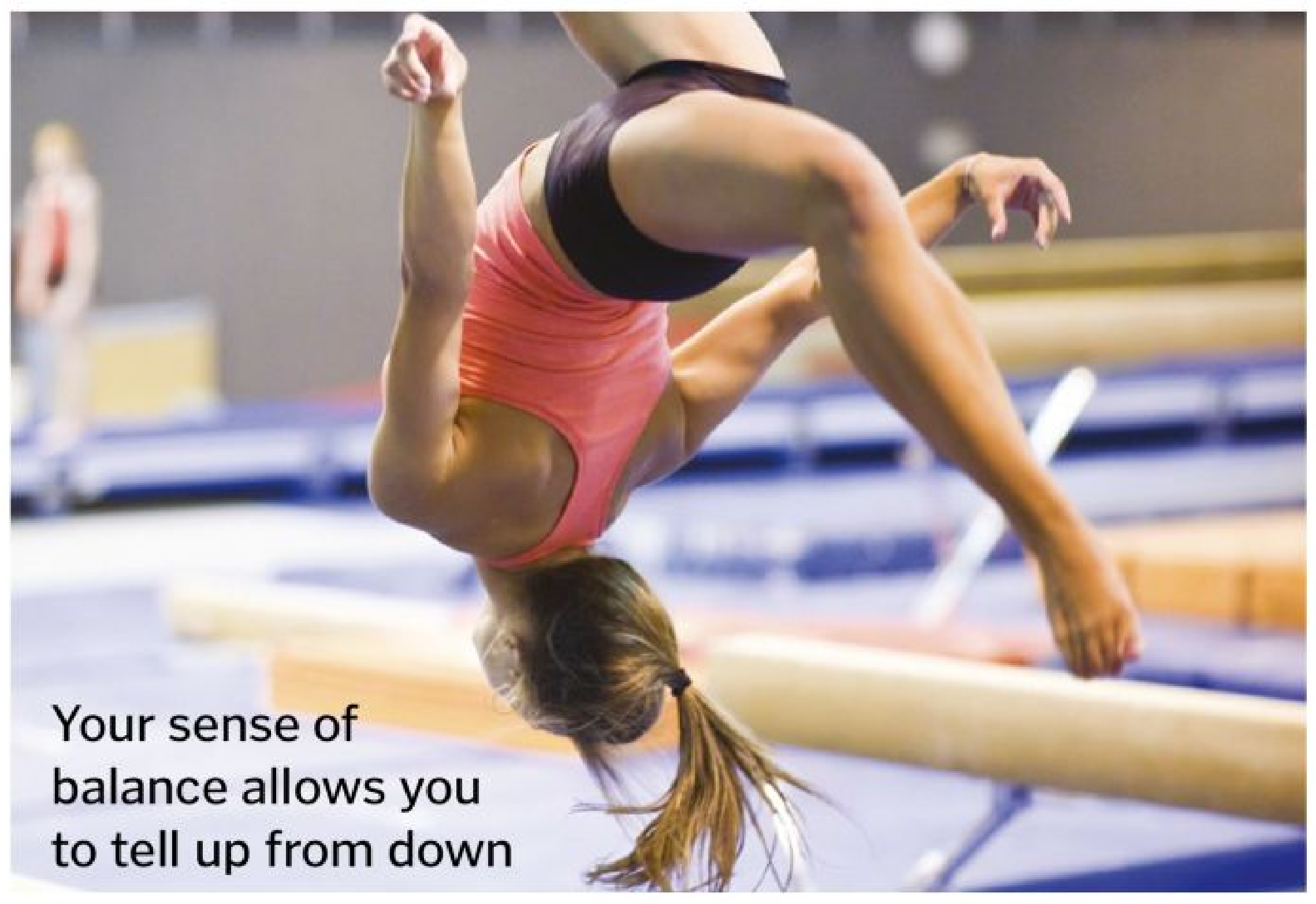
Birds abandon chicks touched by humans

25 Birds have keen eyesight but a poor sense of smell, so there is no evidence that the scent of a human would result in the abandonment of a chick. They are known to abandon their young when they feel threatened, but for most birds it would take more than an approaching human to trigger this behaviour.

Pears contains the toxic preservative formaldehyde

Natural products are safer than man-made

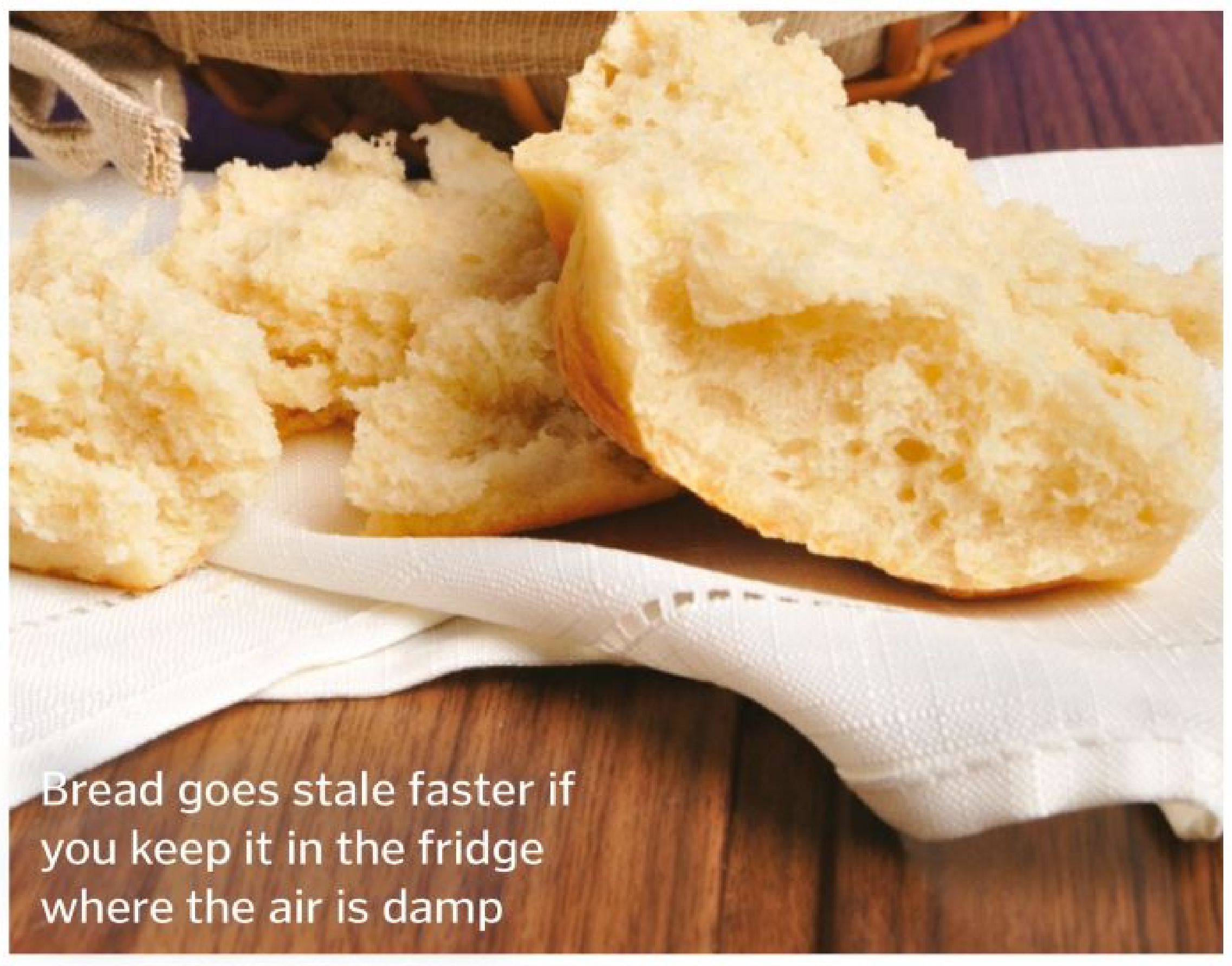
26 There is much scepticism about man-made products and products often advertise themselves as being 'all natural', but there is nothing inherently safe about naturally occurring chemicals. Everything is toxic in a high enough dose, whether man-made or naturally occurring, and how something was made is not as important as what it contains.



Your sense of balance allows you to tell up from down

Humans only have five senses

27 Humans have five main senses: vision, hearing, touch, taste and smell, but the list does not end there. We have many more senses, including equilibrioception, the sense of balance, and nociception, the sense of pain. We also have proprioception, the ability to tell where our bodies are in space, and thermoception, the sense of hot and cold.



Bread goes stale faster if you keep it in the fridge where the air is damp

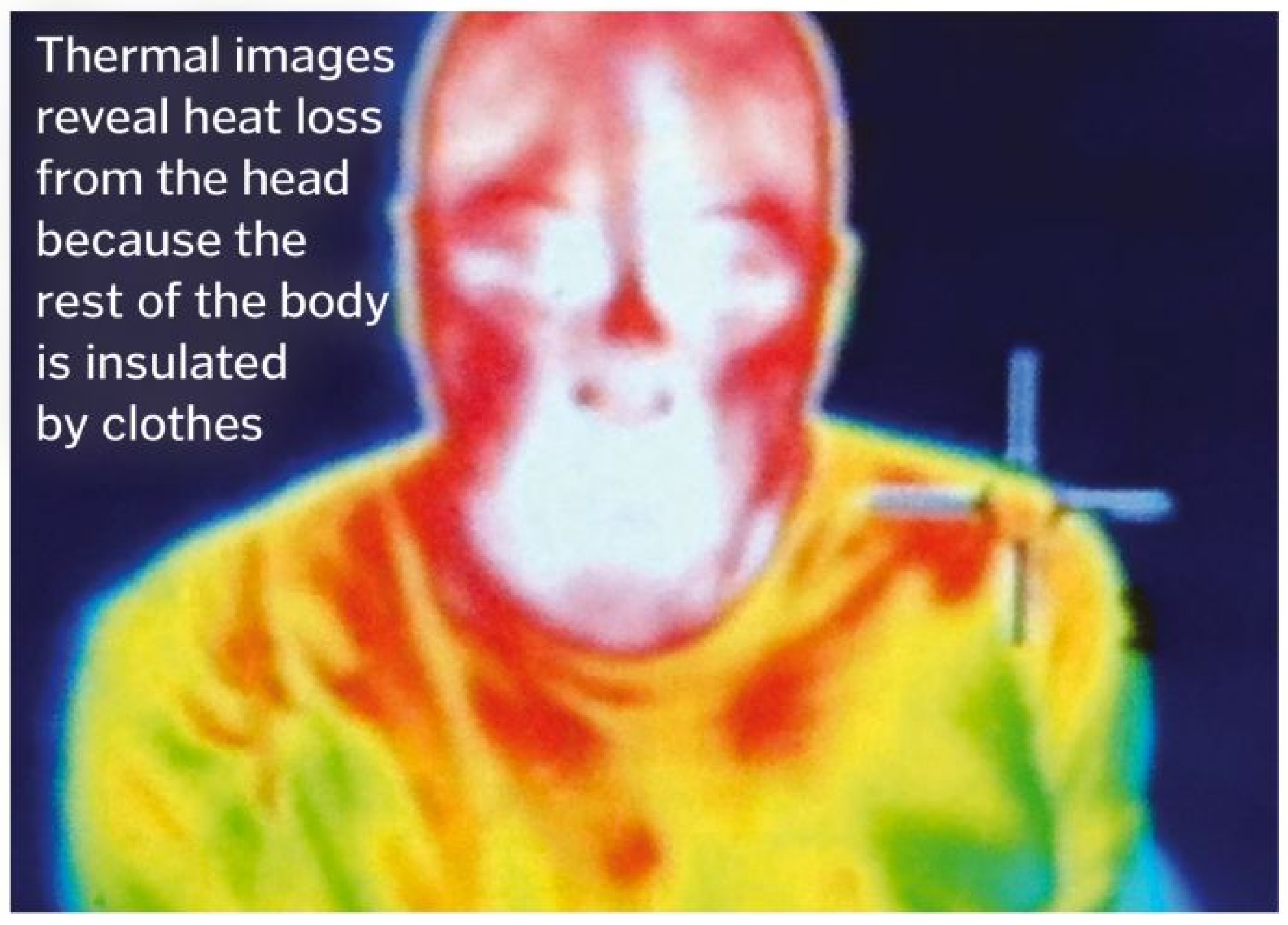
Bread goes stale because it dries out

28 Stale bread feels dry and can be rejuvenated with a splash of water, but it has not dehydrated. Instead, the water has become bound up in hard starch crystals. The process can be slowed down by adding more fat to the bread recipe, or by keeping the bread in a cool, dry place.

Imperfections in old glass windows and bottles were there when the objects were first made

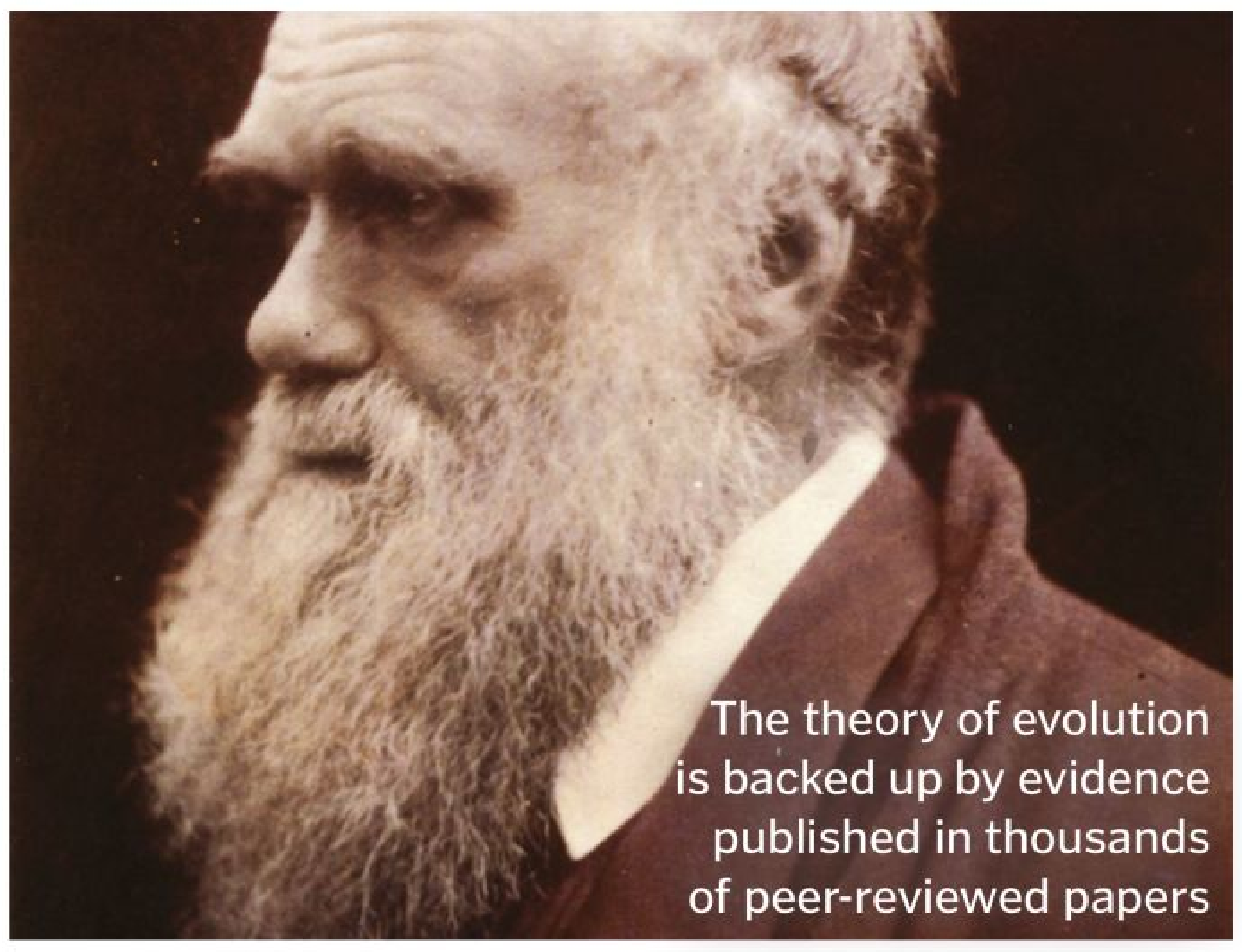
Glass pools at the bottom of windows

29 Old windows are often thicker at the bottom than they are at the top, and it was once thought that glass was as a slow-moving liquid. However, glass is now classified as an elastic solid, and according to chemists and glass experts, any imperfections in old windows were introduced at the time they were made.


Thermal images reveal heat loss from the head because the rest of the body is insulated by clothes

You lose most of your heat through your head

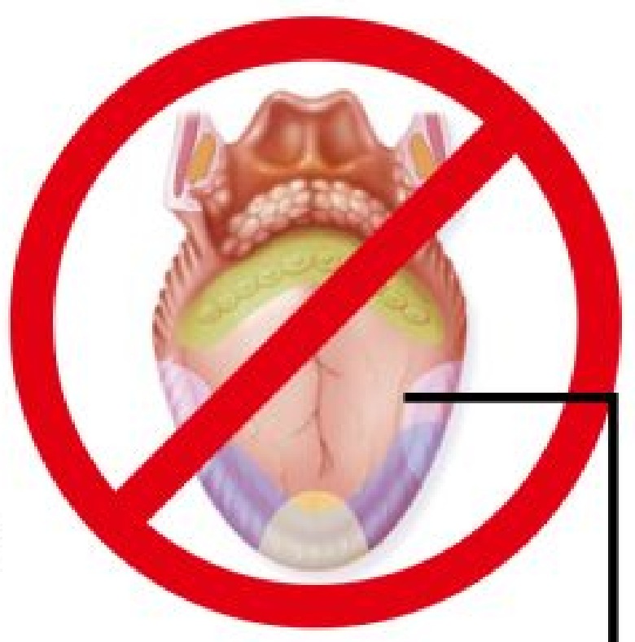
30 In the winter, people are often advised to put a hat on under the pretext that most of your body heat escapes through your head. In fact, there is nothing particularly special about this body part and it loses heat at around the same rate as any other; it's just that the rest of our bodies are often covered with clothes.


The theory of evolution is backed up by evidence published in thousands of peer-reviewed papers

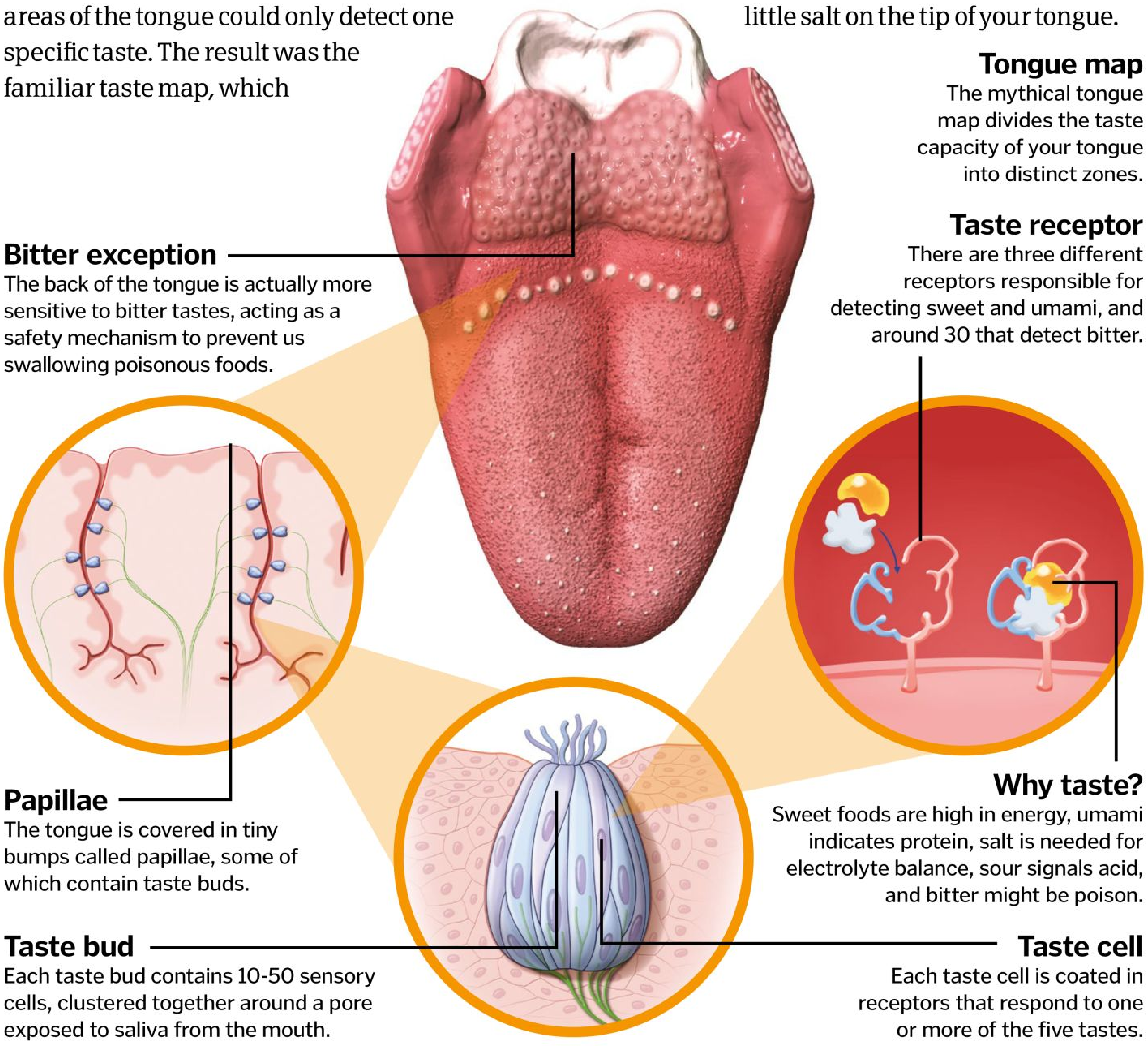
A theory is just an idea

31 In day-to-day usage, the word 'theory' is often taken to mean the same as 'idea', or 'educated guess', and as a result scientific theories like evolution and the Big Bang are sometimes treated with suspicion. In science, a theory is built using evidence, and is close enough to the 'truth' that it can be used to predict what might happen next.

Different parts of your tongue respond to different tastes



32 This myth was born in 1901 when German scientist DP Hanig tested people's responses to different tastes on different parts of the tongue. His test subjects reported they were able to taste certain things better in different areas, but the research was mistranslated, leading people to believe certain areas of the tongue could only detect one specific taste. The result was the familiar taste map, which arranged the surface of the tongue into different zones; the tip detecting sugar, the front sides salt, the rear sides sour and the back of the tongue bitter. Incredibly, it wasn't until 1974 that scientists challenged the well-established myth, even though you can easily disprove it at home by putting a little salt on the tip of your tongue.



Tongue map
The mythical tongue map divides the taste capacity of your tongue into distinct zones.

Taste receptor
There are three different receptors responsible for detecting sweet and umami, and around 30 that detect bitter.

Bitter exception
The back of the tongue is actually more sensitive to bitter tastes, acting as a safety mechanism to prevent us swallowing poisonous foods.

Papillae
The tongue is covered in tiny bumps called papillae, some of which contain taste buds.

Why taste?
Sweet foods are high in energy, umami indicates protein, salt is needed for electrolyte balance, sour signals acid, and bitter might be poison.

Taste bud
Each taste bud contains 10-50 sensory cells, clustered together around a pore exposed to saliva from the mouth.

Taste cell
Each taste cell is coated in receptors that respond to one or more of the five tastes.

The heat of a chilli is in the seeds

33 Many cooks mistakenly believe the hottest part of a chilli is the seeds, when in fact the heat-producing chemical is concentrated in the white pulp that surrounds them. The chemical is known as capsaicin and it activates nerves that normally transmit signals about temperature. Chilli seeds are destroyed in the mammalian digestive system and scientists think the plants produce capsaicin as a deterrent. Birds are unaffected by the fiery chillies and their digestive systems actually help the seeds to germinate.

Shaving causes hair to grow back thicker

34 Shavers are often convinced that their hairs grow back thicker after they have been razored, but there is no evidence to support this idea. The perceived increase in thickness or coarseness of the hairs is actually to do with their shape. Before hairs are cut they have soft, tapered ends, and they tend to fall or curl under their own weight, but when they are trimmed the hairs end abruptly in a sharp, flat cut, which stands upright against the skin.

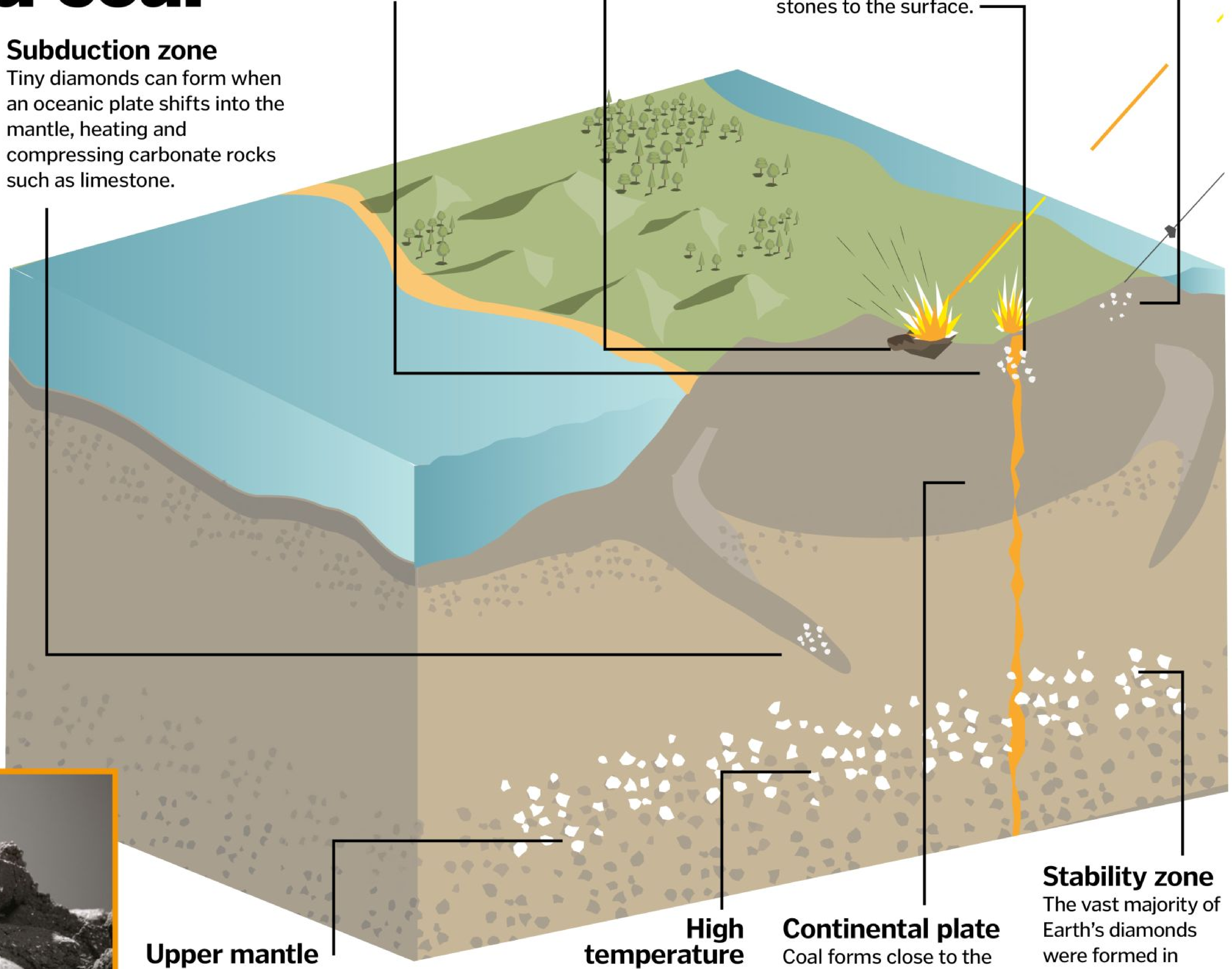
During an earthquake, you should hide in the nearest doorway

35 Doorframes used to be one of the last structural features of a house to collapse during an earthquake, but technological advances have changed the way that modern houses are built and it is no longer the safest place to stand. New advice recommends dropping to the floor and curling up, preferably beneath a sturdy piece of furniture like a bed or a table, and protecting your head and neck with your arms.

© Science Photo Library; Alamy; Dreamstime; Thinkstock

Diamonds are made from compressed coal

36 Diamond and coal are both formed from carbon, but it is not true that one is made from the other. Coal is formed from the remains of prehistoric plants and tends to be found around 3.2 kilometres (two miles) below the surface of the Earth, while most diamonds are formed from carbon-containing minerals found in the upper mantle, around 150 kilometres (90 miles) beneath the ground. The diamonds are delivered to the surface by a rare form of volcanic activity known as a deep-source eruption, which pushes upward through the mantle carrying the diamonds toward the surface and traps them in a pipe of igneous rock.



Subduction zone
Tiny diamonds can form when an oceanic plate shifts into the mantle, heating and compressing carbonate rocks such as limestone.

Coal diamonds
It is possible that coal near the surface could be transformed into diamonds at subduction zones and asteroid impact sites.

Asteroid impact
When asteroids slam into the Earth, the impact heats and compresses the crust and can form tiny diamonds.

Deep-source eruption
Volcanic eruptions beginning deep underground shoot through diamond-forming regions and carry the stones to the surface.

Meteorite fall
Diamonds can form in space, as tiny nanodiamonds have been found inside fallen meteorites.

Upper mantle
Most diamonds form deep inside the Earth's mantle, well below any coal deposits.

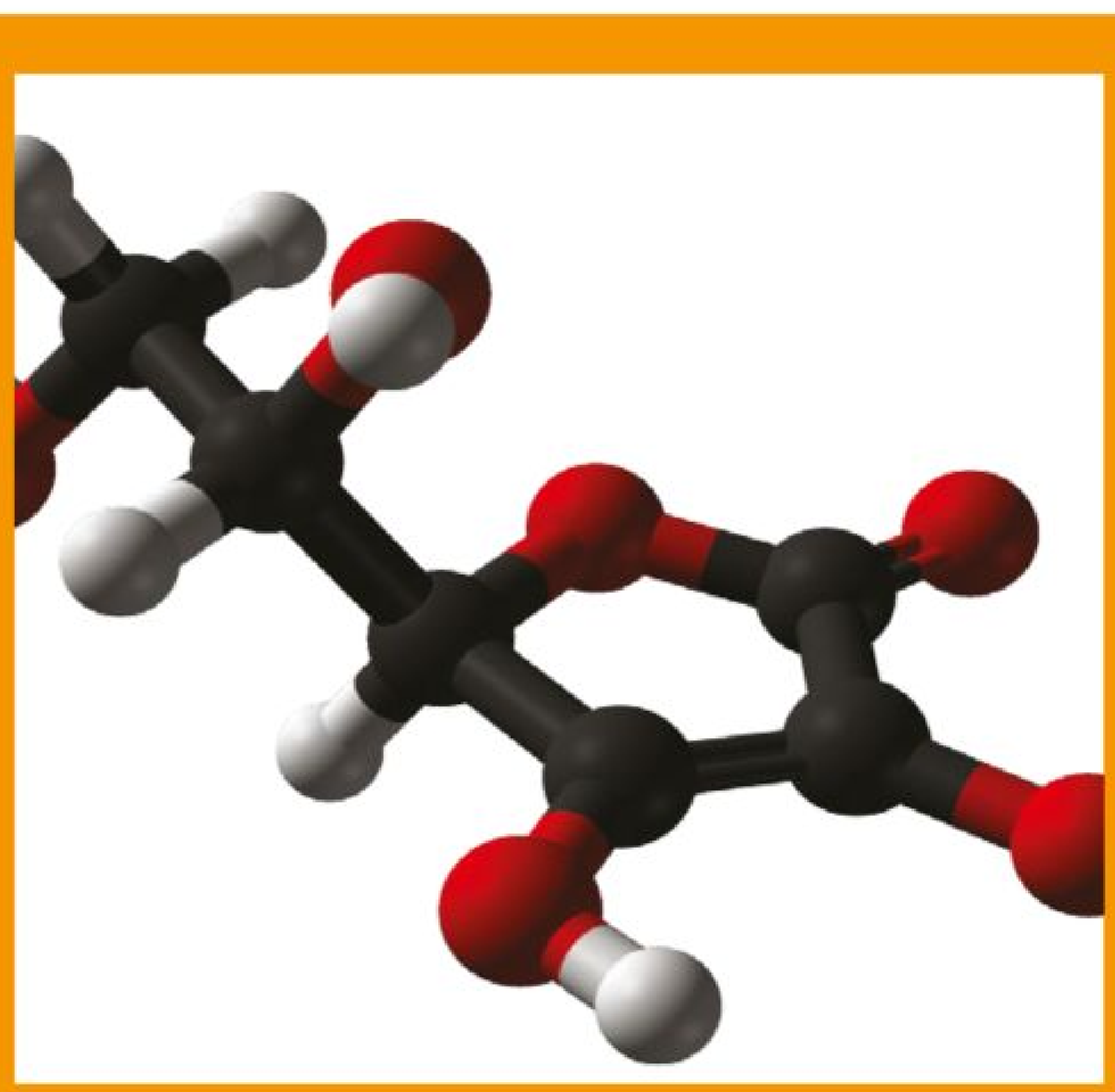
High temperature
At this depth, the temperature exceeds 1,050°C (2,000°F).

Continental plate
Coal forms close to the surface, within the tectonic plates that make up the Earth's crust.

Stability zone
The vast majority of Earth's diamonds were formed in stability zones beneath the continental plates.

Close-up TV harms your eyes

37 There is no evidence that sitting too close to the television is bad for your eyesight; however, the myth is not completely unfounded. Although moving closer to watch your favourite programmes does not cause near-sightedness, it could indicate an underlying problem with your eyesight.

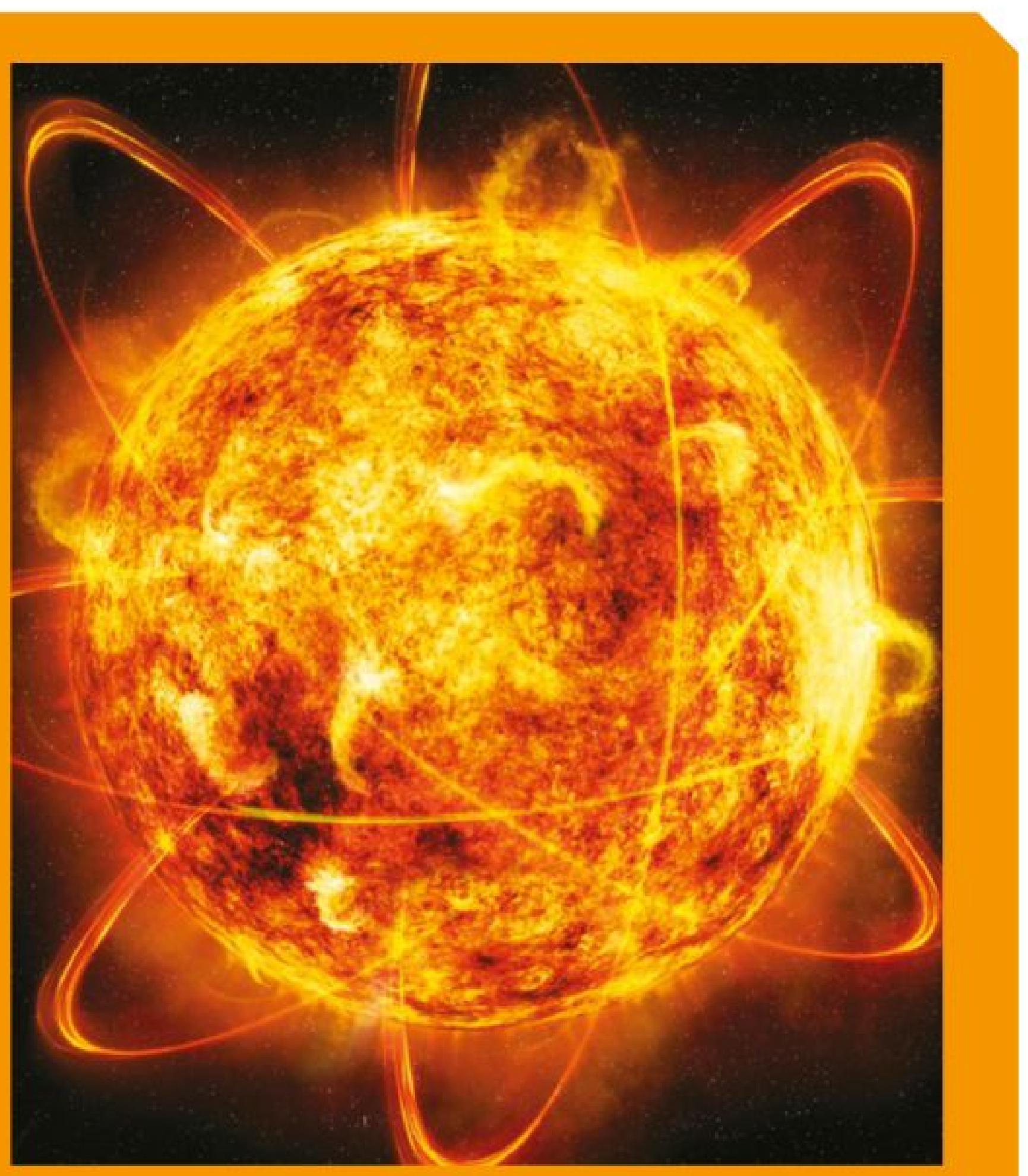


Vitamin C protects you from illness

38 Many people choose to load up on vitamin C supplements in the winter in an effort to stave off the common cold, but there is little evidence that it actually works. In a large-scale study of over 11,000 people, scientists found no significant difference between people who took daily supplements and those who did not.

Hens need a rooster to lay eggs

39 It is a common misconception that hens need a rooster in order to lay eggs. Hens are able to store sperm inside their bodies, allowing eggs to be fertilised before they are laid. If there is no sperm available, the eggs are still produced and are laid even though they will not develop into chicks.

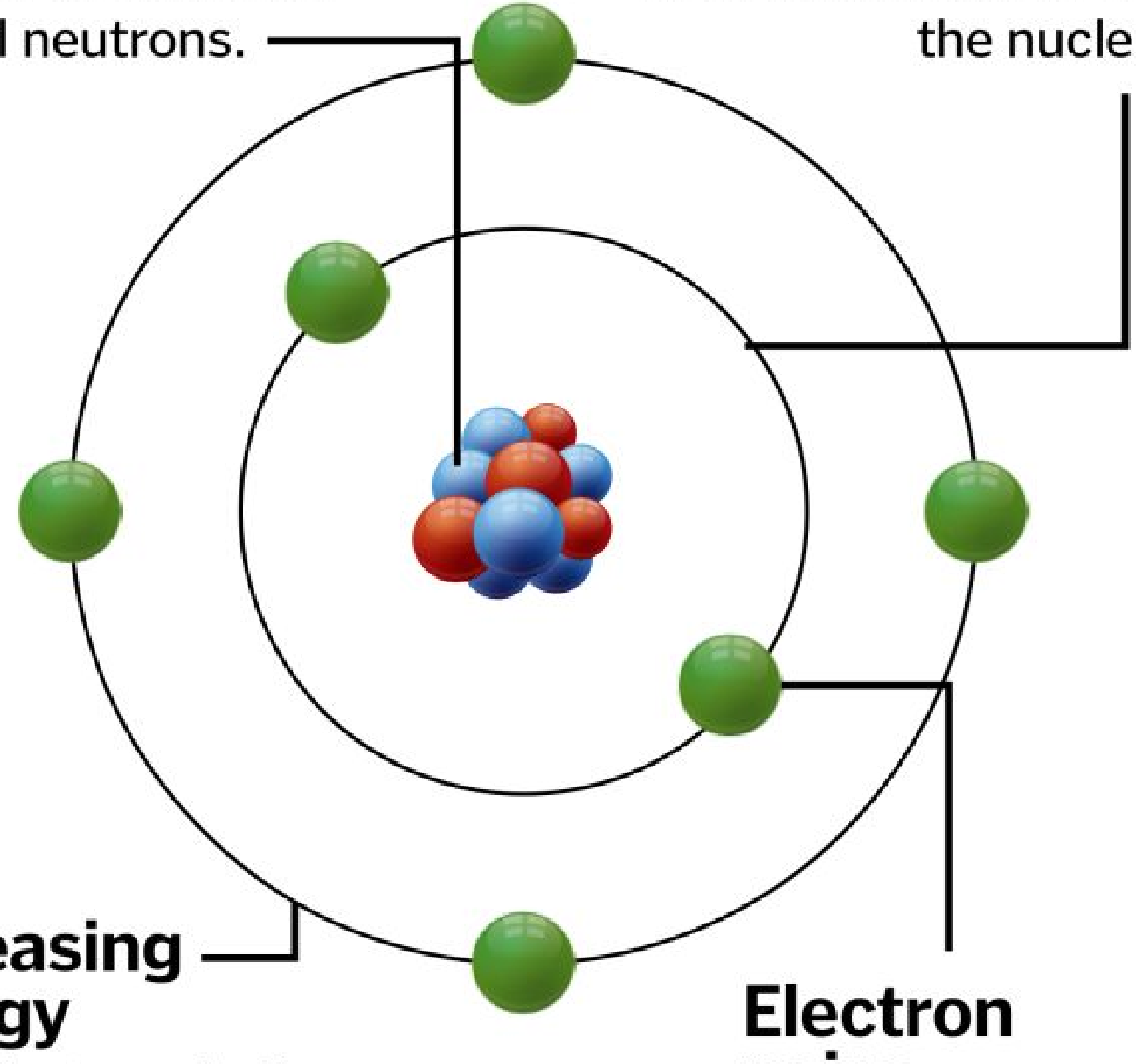


The Sun is burning

40 The Sun might look like a ball of fire in the sky, but it is not really burning. The Sun is a nuclear fusion reactor, and the light and heat that it emits is the result of energy released when hydrogen atoms slam together and fuse to form helium.

Electrons orbit atomic nuclei like planets orbit the Sun

41 Looking at the standard textbook image of the atom, it is easy to imagine that the electrons orbit the nucleus in circles, like planets revolving around the Sun, but the diagrams are misleading. Rather than representing the orbits of the electrons, these images show their energy levels. In reality, we cannot know where an electron is and where it is going at the same time, so it is not possible to map out the path they take around the atomic nucleus. Instead, physicists map three-dimensional regions of space known as orbitals, which predict where each electron is likely to be.

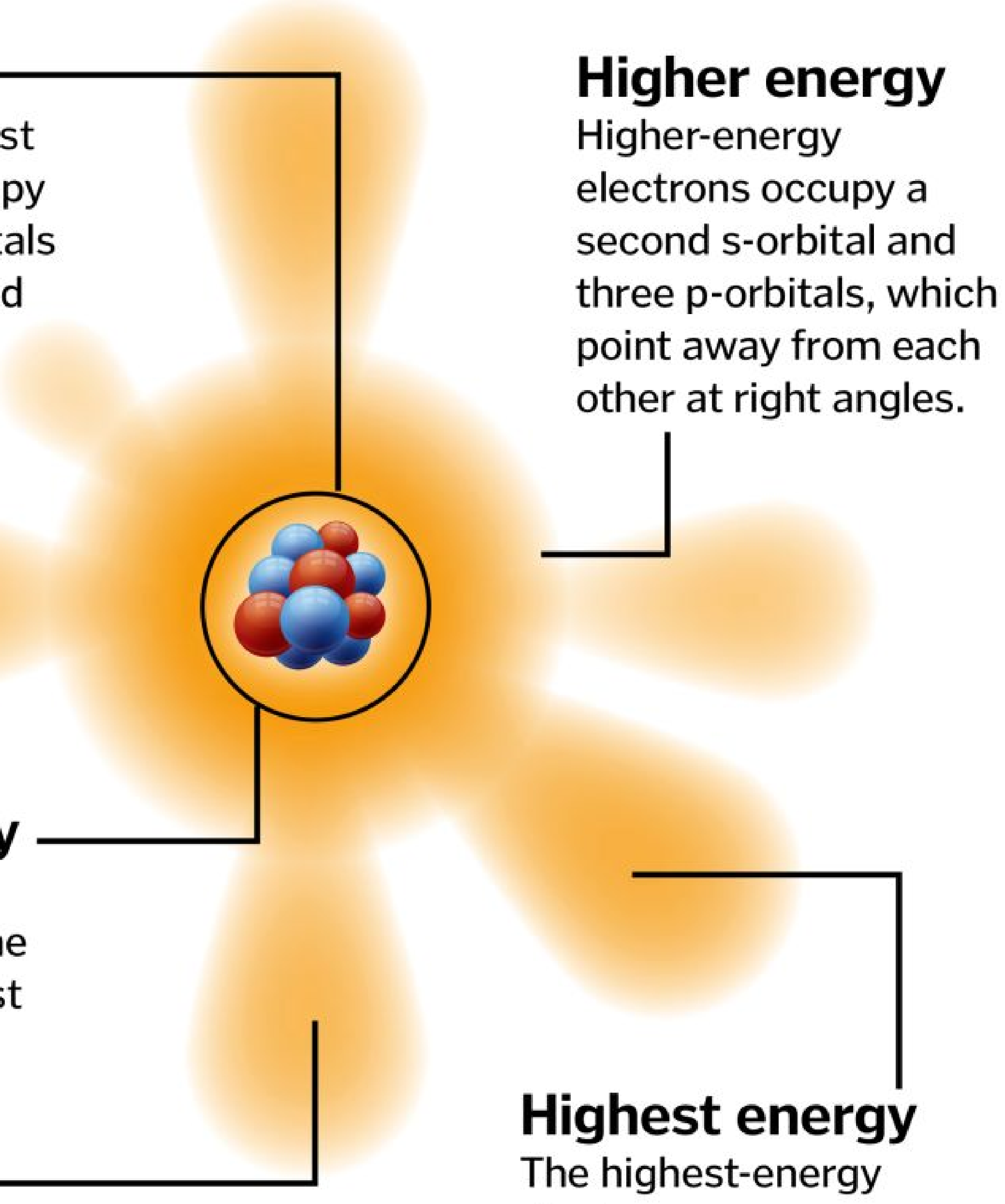


Atomic nucleus
The nucleus of an atom is made up of positively charged protons and neutral neutrons.

Electron shells
In standard images, the electrons are arranged in circular shells around the nucleus.

Increasing energy
Each electron shell represents a different energy level; those farther from the nucleus are at a higher energy level.

Electron pairs
Each orbital has room for one pair of electrons.



S-orbital
The electrons closest to the nucleus occupy symmetrical s-orbitals and tend to be found in a sphere close to the nucleus.

Higher energy
Higher-energy electrons occupy a second s-orbital and three p-orbitals, which point away from each other at right angles.

Lowest energy
The lowest-energy electrons occupy the first s-orbital closest to the nucleus.

P-orbital
Some electrons are found in p-orbitals, which resemble pairs of balloons pointing away from one another.

Highest energy
The highest-energy electrons occupy more layers of p-orbitals and additional d and f-orbitals.

Baking soda absorbs smells

42 Baking soda is a common kitchen ingredient that reacts with acids like vinegar to produce bubbles of carbon dioxide. It is hailed as a deodoriser because it can also neutralise smelly acids, like those found in sweat. However, on non-acidic smells it makes little difference, and as it absorbs water from the air it forms a crust that prevents its acid-neutralising action.

Salt makes water boil quicker

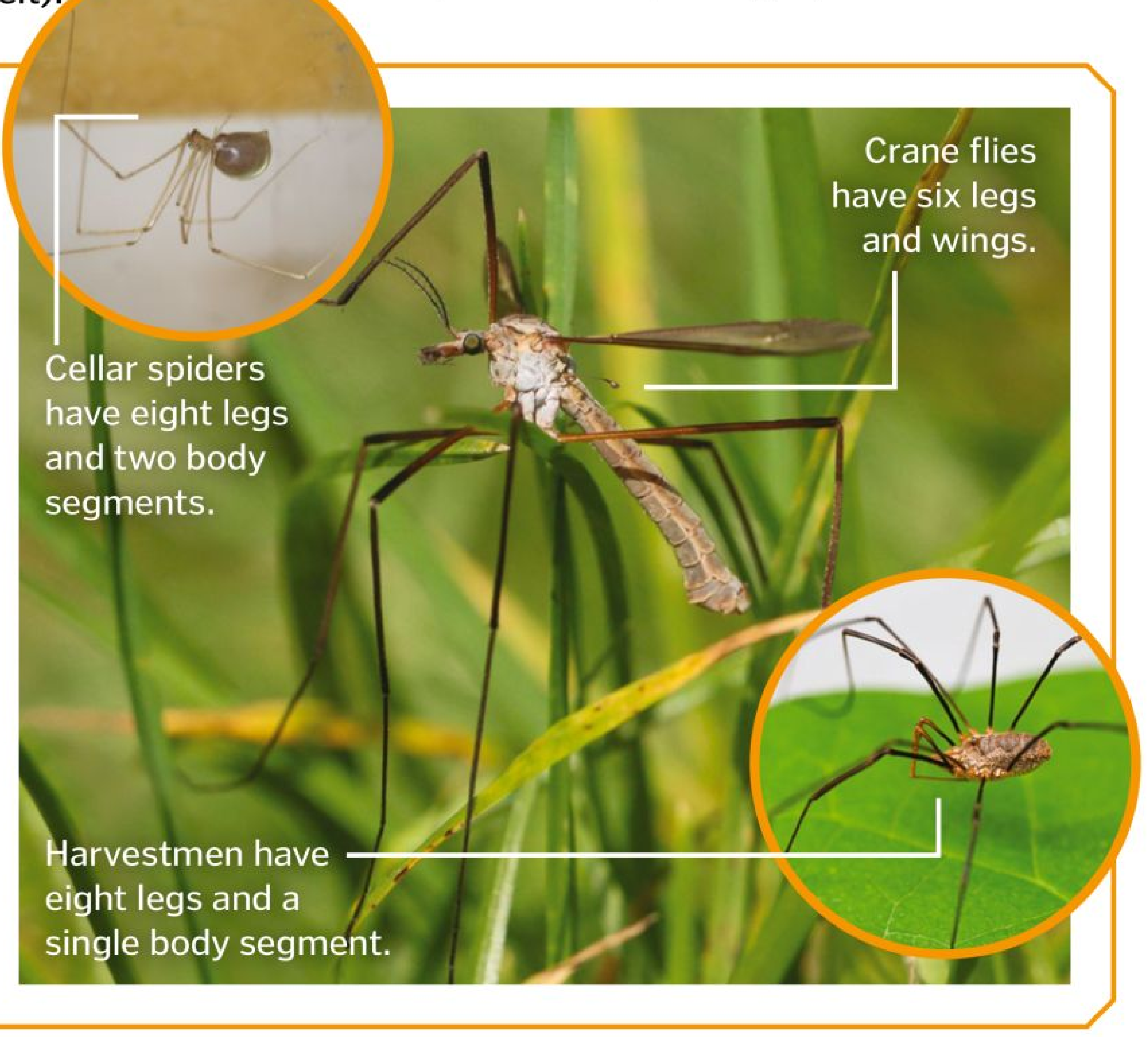
43 People add salt to their cooking water in the hope that it will boil faster, but it actually makes the water boil at a higher temperature. In the kitchen this effect is barely noticeable; it takes about 230 grams (8.1 ounces) of salt to increase the boiling point of one litre (0.26 gallons) of water by just two degrees Celsius (3.6 degrees Fahrenheit).

Some people have photographic memories

44 Many people have claimed to be able to recall an image in perfect detail, but no case has ever been confirmed. Some people are able to hold an image in their mind for a short time after it has been taken away, a phenomenon known as eidetic memory, but the picture is not as perfect as a photograph.

Daddy long legs are the most venomous spiders, but they cannot bite through your skin

45 There are three different invertebrates people commonly know as 'daddy long legs', crane flies, harvestmen and cellar spiders. Cellar spiders are venomous, and their fangs are anatomically similar to those of brown recluse spiders, which are capable of biting people, but there is no evidence that their venom is powerful enough to kill a human. Harvestmen and crane flies are not spiders and have neither fangs nor venom.



Cellar spiders have eight legs and two body segments.

Crane flies have six legs and wings.

Harvestmen have eight legs and a single body segment.

The Moon has a dark side

46 The moon is tidally locked to the Earth, meaning we always see the same side of its surface, but the other side is not in permanent shadow. Like the Earth, the Moon turns on its axis and all of its surface experiences both day and night.

Popping candy could burst your stomach

47 Popping candy is made by mixing molten sugar syrup with pressurised carbon dioxide gas. When the candy melts in your mouth, trapped bubbles release their pressure with a pop. The amount of gas released is very small and stories of children dying after eating a combination of popping candy and carbonated drinks are merely urban legend.

Fur and hair are different

48 Despite names and appearances, there is no real difference between the fur and hair. Both are both made from exactly the same material, keratin, and they are both produced by follicles in the skin. In fact, fur and hair are the same as eyelashes, whiskers and even porcupine quills.

Oil is not attracted to water

49 Amazingly, oil molecules are more strongly attracted to water than they are to one another, (which is why an oil droplet will spread out across the surface and does not stay together as a ball). The reason the fluids do not mix is because the water molecules are more strongly attracted to each other than they are to the oil.

Club soda is a miracle stain remover

50 Carbonated water is hailed as a miracle stain remover, but it turns out it is no better than plain water for removing an unwanted mess. Some people claim the bubbles contribute to loosening the stain from the fabric, but in head-to-head cleaning tests both liquids are equally effective.

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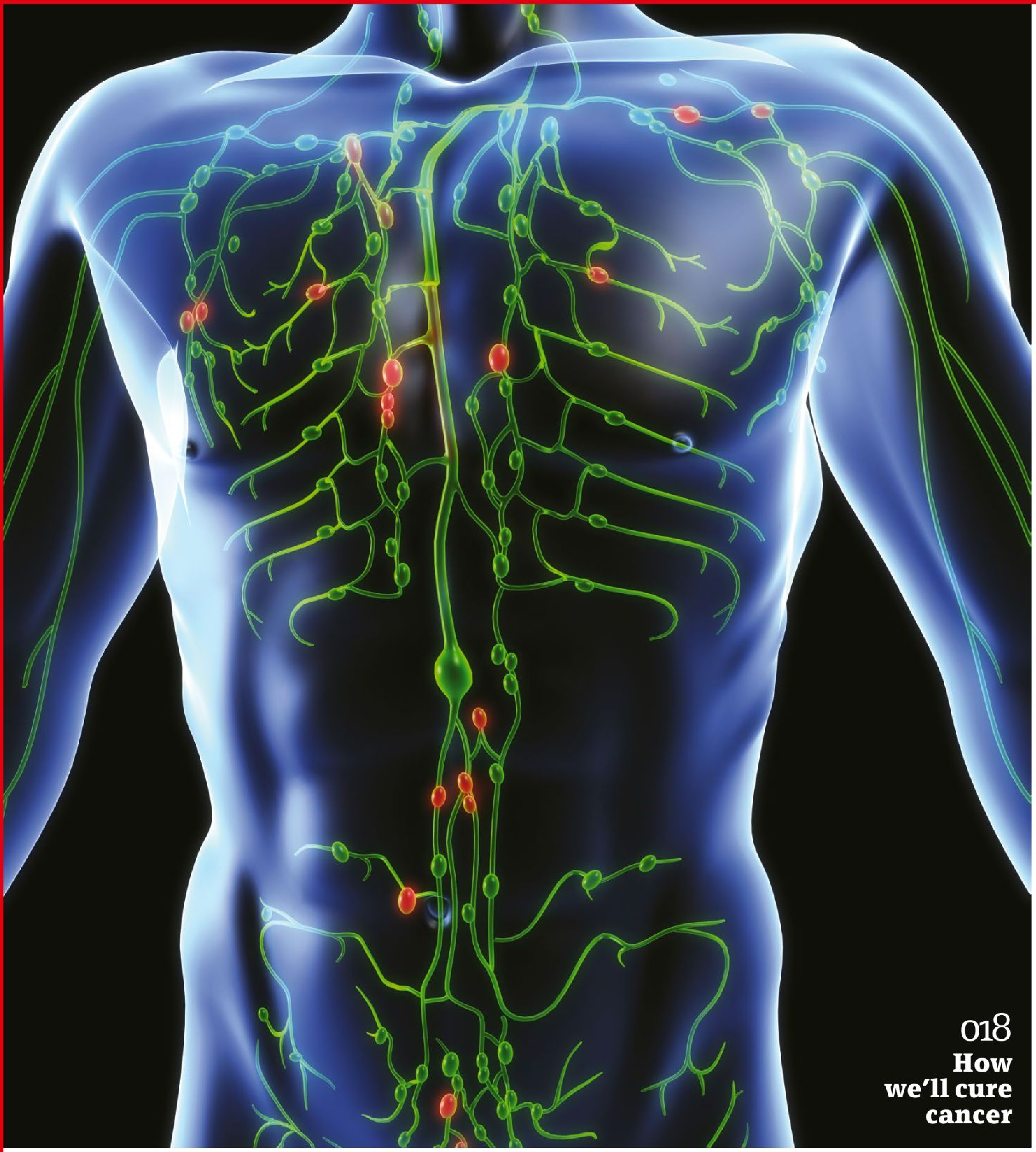
BIOLOGY



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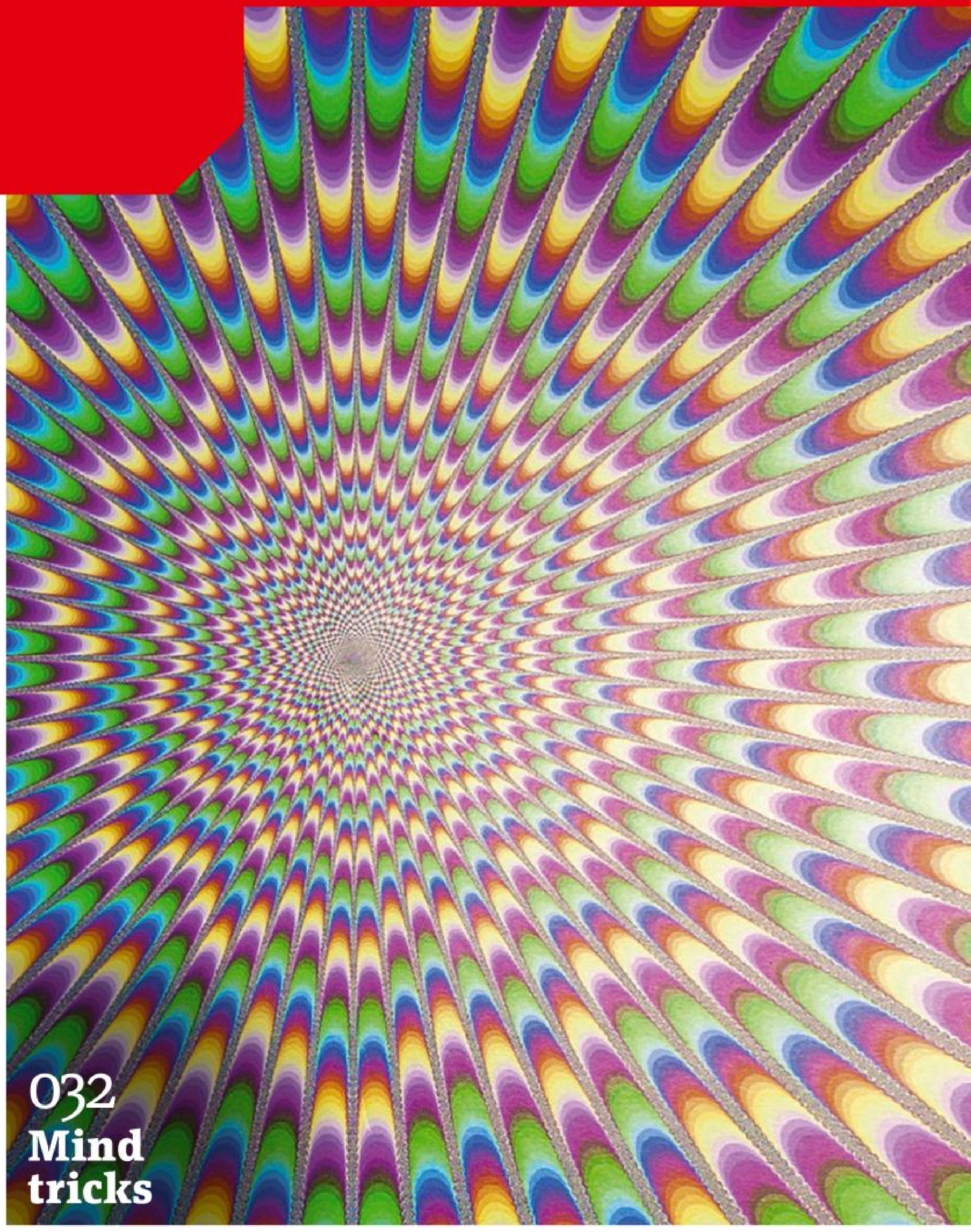
How we'll cure cancer



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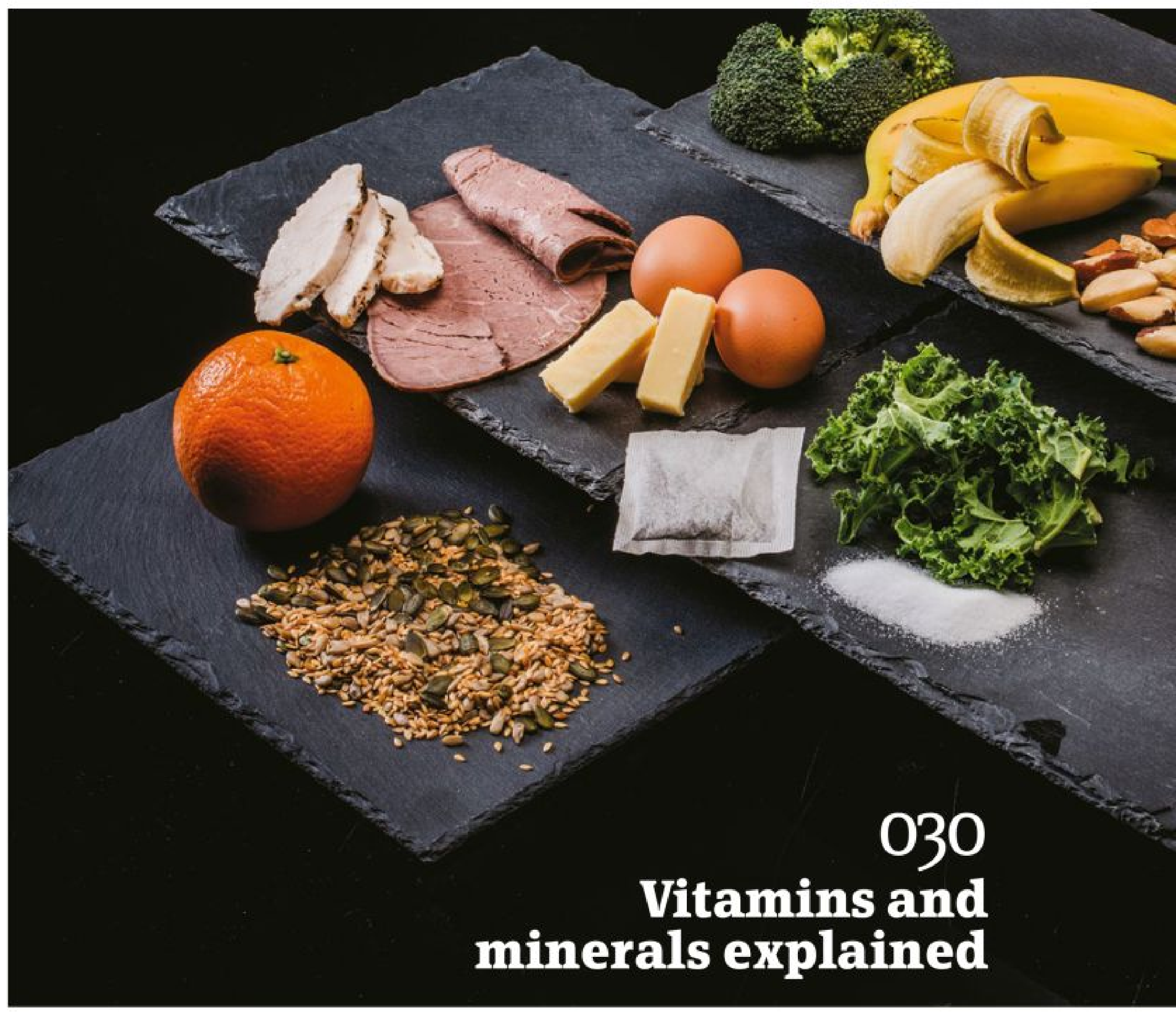
Mind tricks



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Vitamins and minerals explained

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028 How vaccines work
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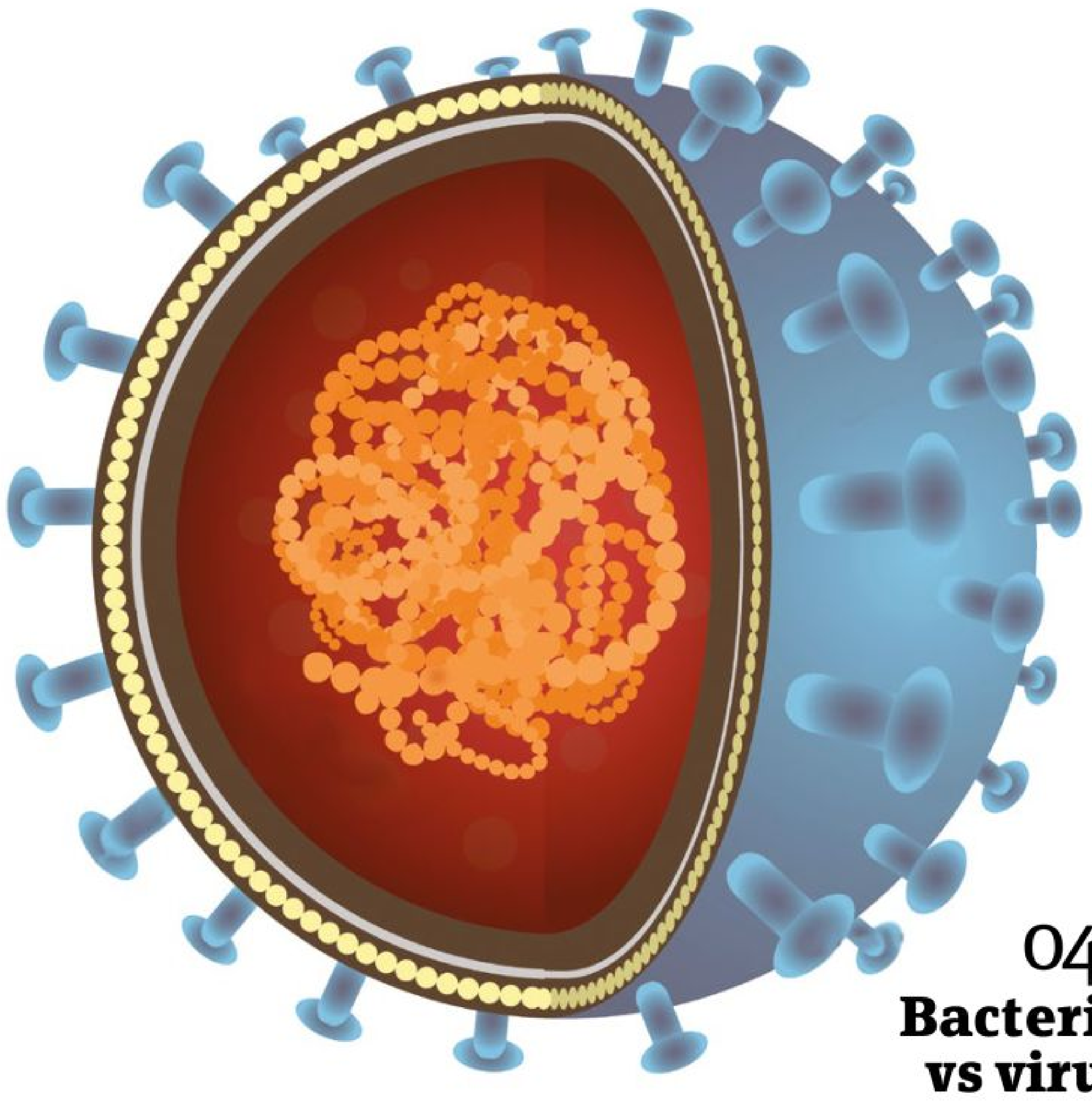
064 Types of headache
064 How clean are your teeth?
065 Anatomy of facial expressions

042
The human brain

058
Science of stress



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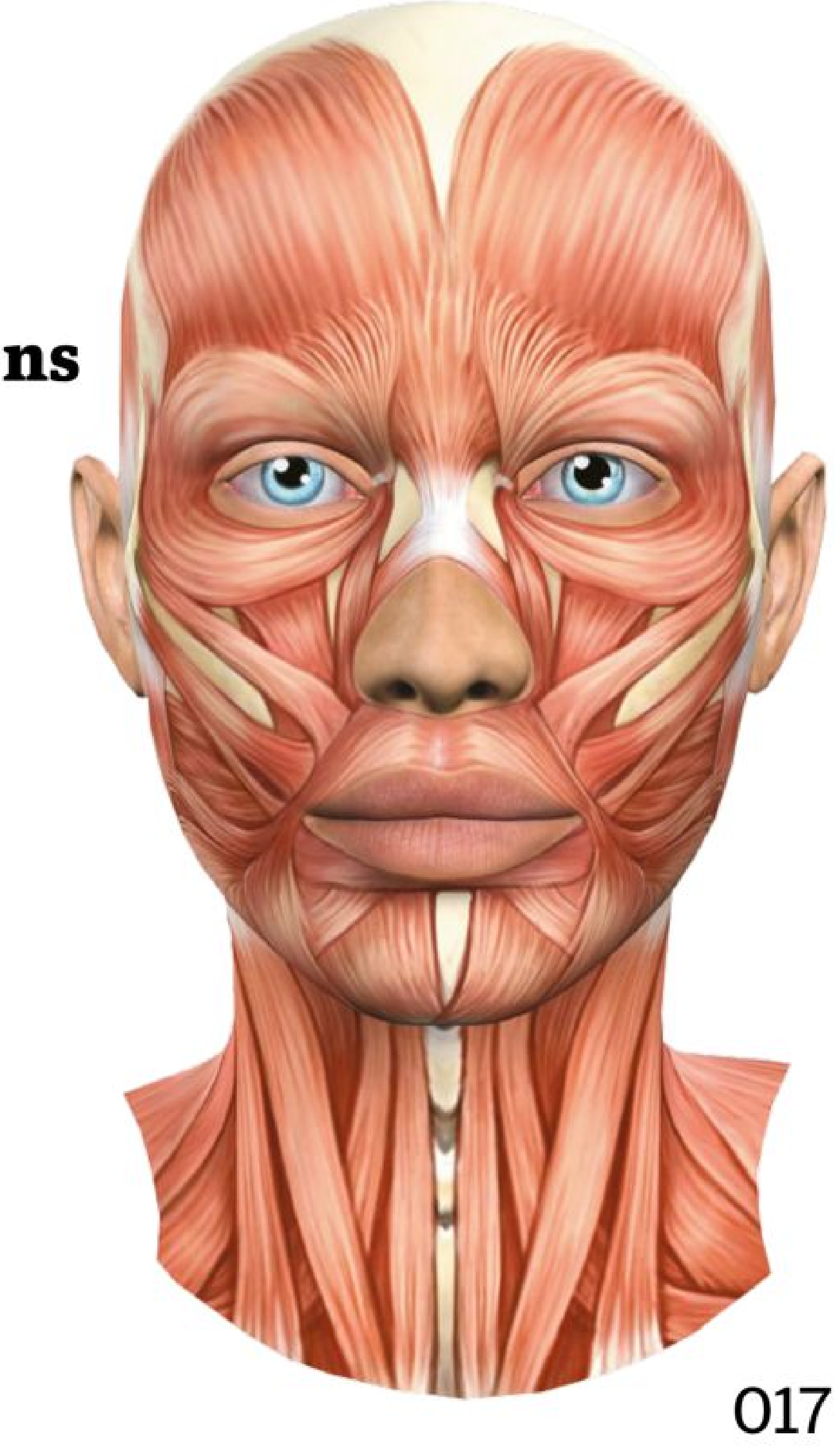
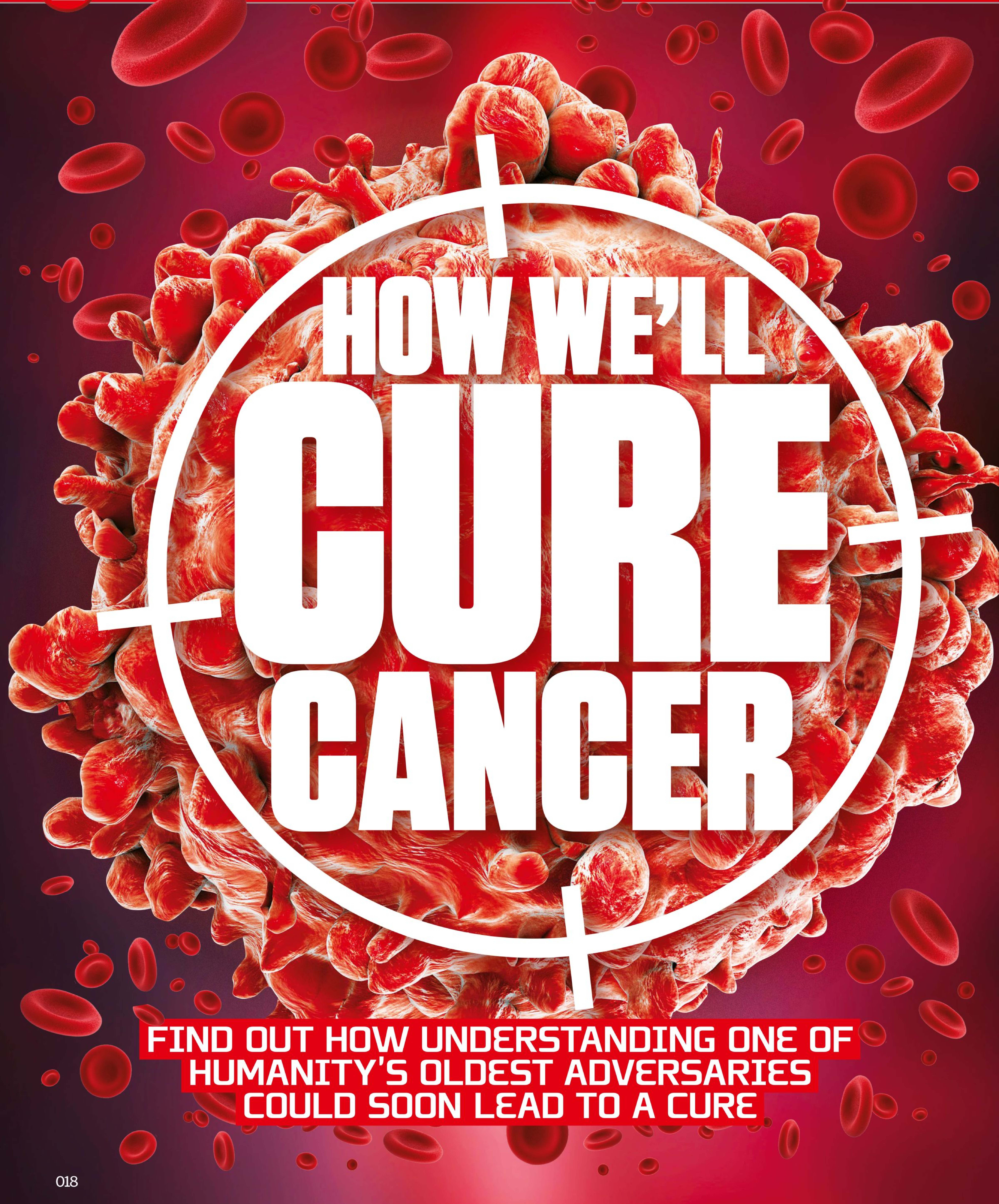




HOW WE'LL CURE CANCER

FIND OUT HOW UNDERSTANDING ONE OF HUMANITY'S OLDEST ADVERSARIES COULD SOON LEAD TO A CURE

Cancer has been around longer than we have. Traces have been found in 70 million-year-old dinosaur bones, in a 120,000-year-old Neanderthal rib, and in a human skeleton dating back to 1200 BCE. And almost every animal, even sharks and naked mole rats, can get the disease.

It was once untreatable. Ancient Roman doctor Celsus wrote, "After excision, even when a scar has formed, none the less the disease has returned." Even if the tumours were removed, they kept coming back, but in ancient times we didn't fully understand exactly what we were up against.

By the 17th century, physicians were pointing the finger at a straw-coloured liquid called lymph, which passes through the body in channels that run alongside the blood vessels. And by the mid-1800s, it became clear that cancers were actually made from cells.

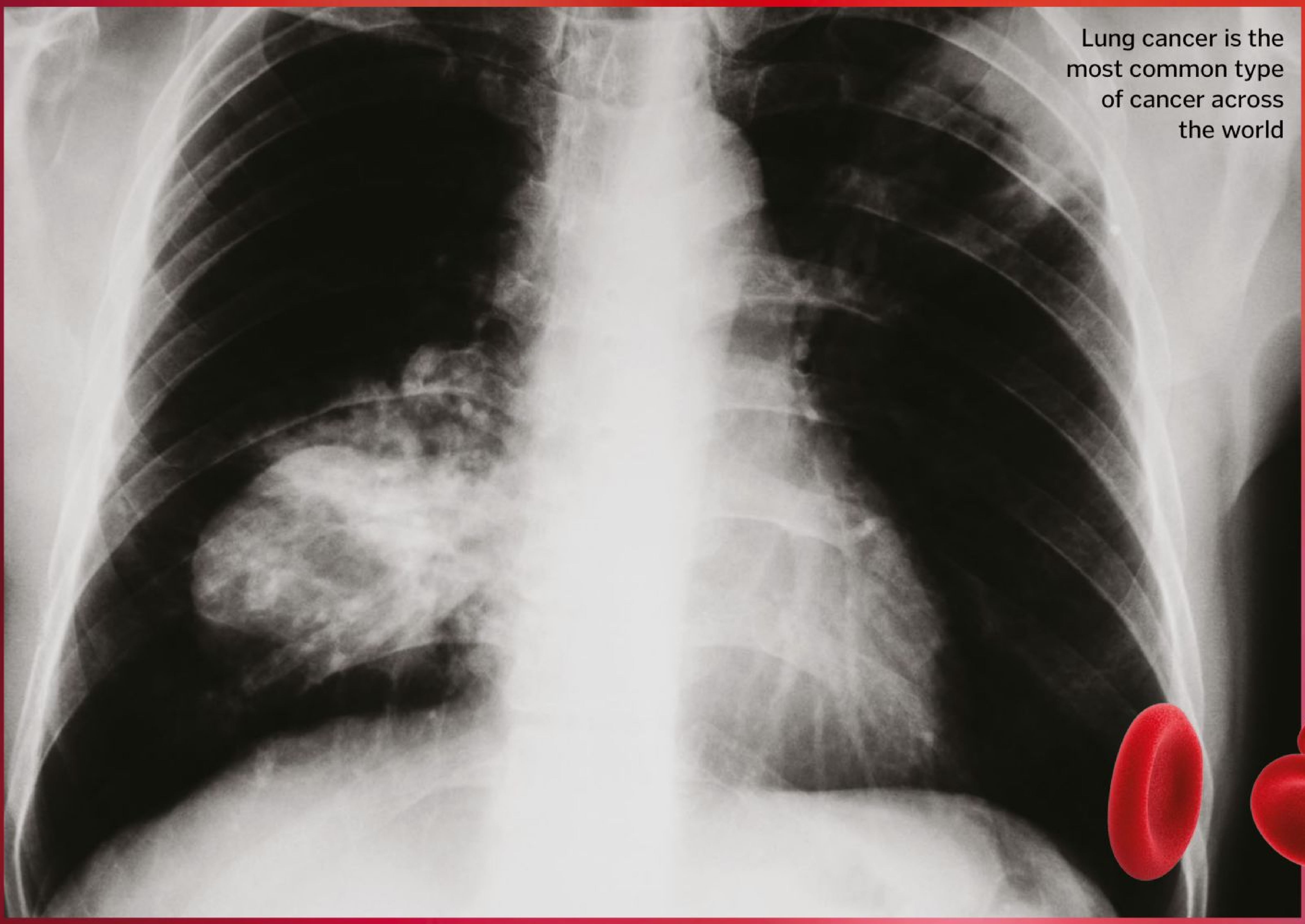
Realising that cancer spread from the original tumour, 19th-century surgeons, with the help of new anaesthetics, started removing more tissue and nearby lymph nodes. Then, at the start of the 20th century, radiotherapy became available to treat irremovable cancers. Nitrogen mustards then became the first chemotherapy drugs after WWI.

Then a massive breakthrough was made. In 1953, James Watson and Francis Crick deciphered the structure of DNA, opening the door to a new era of genetic science. We now know that tumours are made of our own cells but their genes have gone wrong. They change constantly, they evolve to escape treatments, and they hide and spread undetected. And the more we learn, the more we are unravelling their weaknesses.

A century ago a cure for cancer would have been unthinkable, but as research continues survival is rising, and there are many more discoveries yet to be made.

> "Watson and Crick deciphered the structure of DNA"

Damage builds up in our DNA over time, making cancer more common in older people



Lung cancer is the most common type of cancer across the world

Cancer statistics

14 million people were diagnosed with cancer in 2012

22% of cancer deaths are caused by smoking

8.2 million people died from cancer in 2012

70% of cancers happen in low and middle income countries

Cancer is the second highest cause of death in the world

Up to half of all cancers can be prevented by lifestyle changes

Lung cancer is the most common worldwide, followed by breast and colon

The UK has the 23rd highest cancer rate in the world

© Getty; Thinkstock

What is cancer?

The first step to finding a cure is understanding exactly what we're up against

You're made up of an estimated 37.2 trillion cells, each containing an entire copy of your DNA, which consists of 23 pairs of chromosomes and 21,000 genes, written in combinations of four chemical 'letters': A, C, G and T.

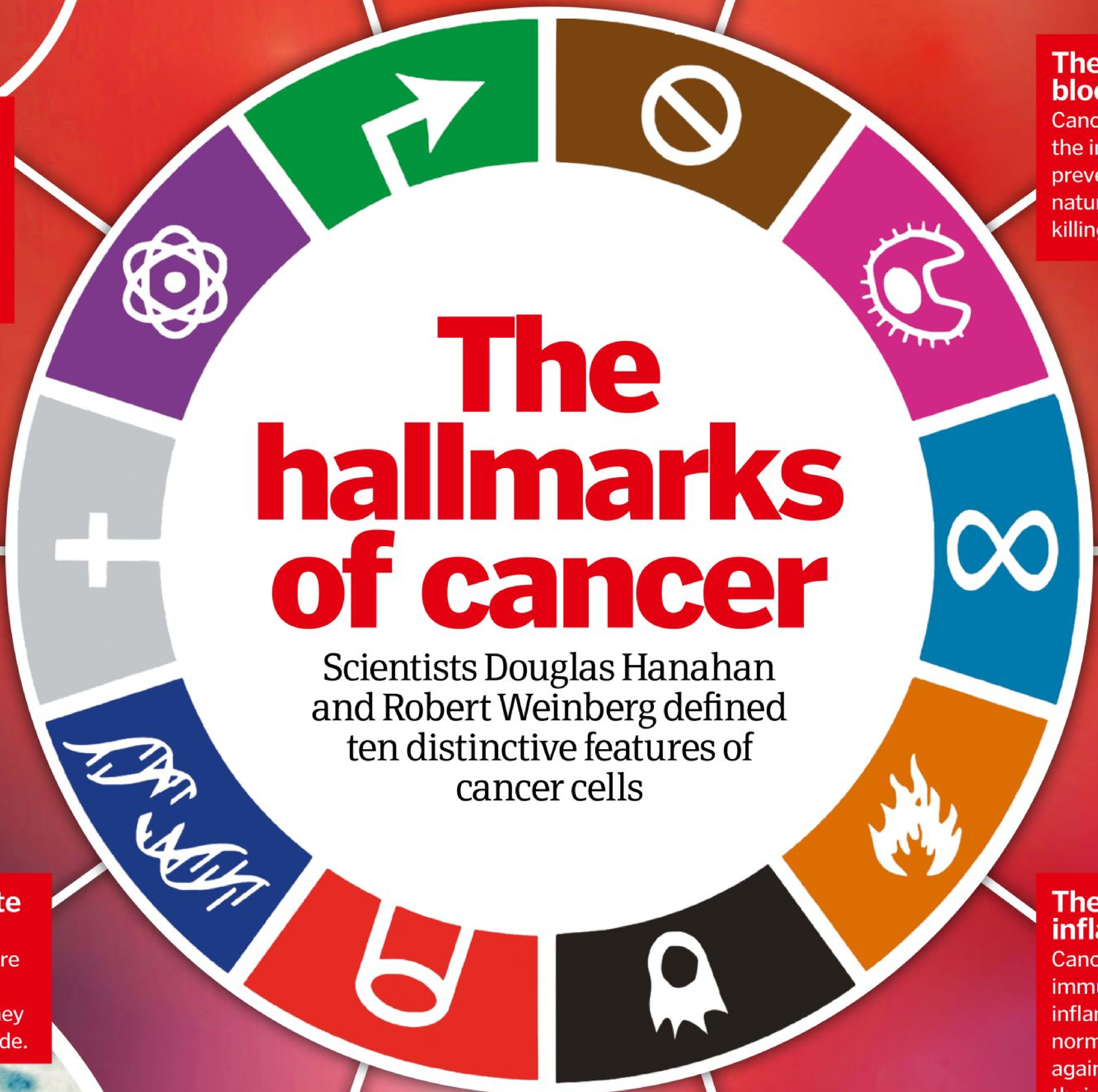
The full human DNA sequence contains around 3 billion letters, and the genes are arranged into three-letter 'words' called codons. Each word corresponds to a molecular building block called an amino acid and, when genes are read in order, the words in a gene provide the recipe to build a protein. Proteins are crucial for everything that a cell does, from making energy to deciding when to divide to communicating with its neighbours. But in cancer cells vital genes contain mistakes, changing their proteins and altering the way that they behave.

It takes lots of genetic mistakes to turn a healthy cell into a cancer cell, and they tend to build up over time. A few people inherit genetic faults from their parents, but most occur as we get older. Sunlight, alcohol, radiation and smoking, for example, can all cause harm to our genetic code. But even people with the healthiest lifestyles accumulate genetic faults.

Cells divide for growth and repair, making copies of themselves to replace old cells or to heal wounds. In order to do this, a cell must first duplicate all 3 billion letters of its DNA, and doing this without making a single mistake is a virtually impossible task.

The copied code is scanned for errors, and mistakes are usually fixed before the cell

> "Cancer cells keep making copies of themselves with more mistakes"



The hallmarks of cancer

Scientists Douglas Hanahan and Robert Weinberg defined ten distinctive features of cancer cells

They keep growing
Cells normally wait for a signal to divide, but cancer cells make their own growth signals.

They don't stop when told
Cancer cells ignore signals telling them to stop dividing.

They avoid white blood cells
Cancer cells hide from the immune system, preventing the body's natural defences from killing them.

They are immortal
Normal cells stop dividing when they become old, but cancer cells keep on replicating indefinitely.

They create inflammation
Cancer cells hijack immune cells, using inflammation that would normally help to fight against an infection to their own advantage.

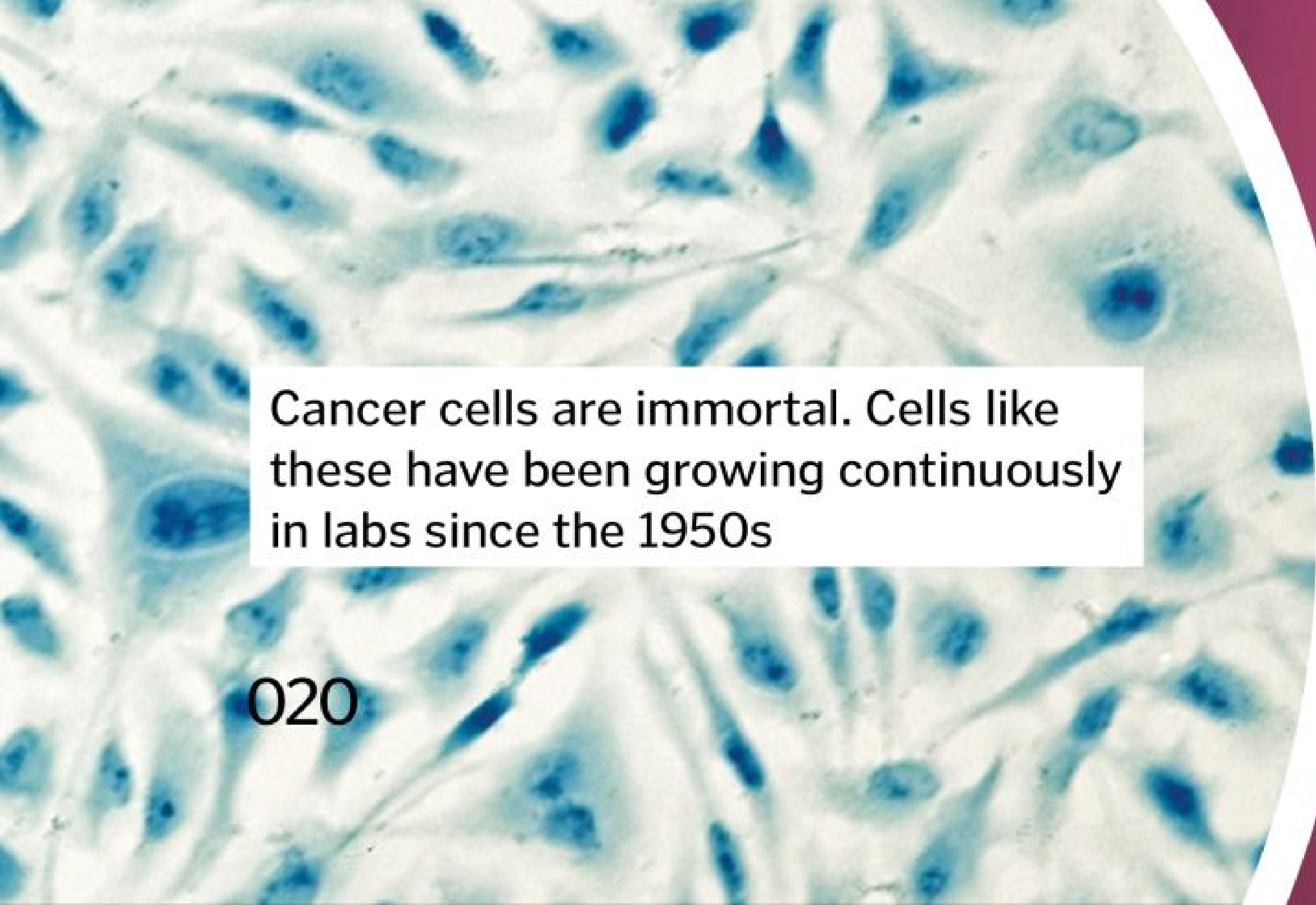
They spread
Cancer cells can spread around the body, creating more tumours in other places.

They set up fuel lines
As tumours grow, they get more oxygen and nutrients by encouraging new blood vessels to form.

They mutate
Cancer cells accumulate more and more mutations as they continue to divide.

They resist death
Healthy cells self-destruct when they are damaged, but cancer cells turn this safety switch off.

They change their metabolism
Cancer cells reprogram their metabolism to keep dividing under conditions that would normally kill other cells.



Cancer cells are immortal. Cells like these have been growing continuously in labs since the 1950s divides, but sometimes errors slip through and over time they start to build up.

Just as changing the letters in a book would make the words unreadable, changing the letters in the genetic code makes it hard for the cell to make sense of its genes. If letters are changed, deleted, added or moved around, it can completely change the meaning of the genetic words, which in turn changes the proteins that the cell makes.

Built-in safety mechanisms normally tell a cell to self-destruct if it has too many genetic errors, allowing a new, healthy cell to take its place. But sometimes damaged cells slip through the net, failing to repair themselves and resisting the signals to die.

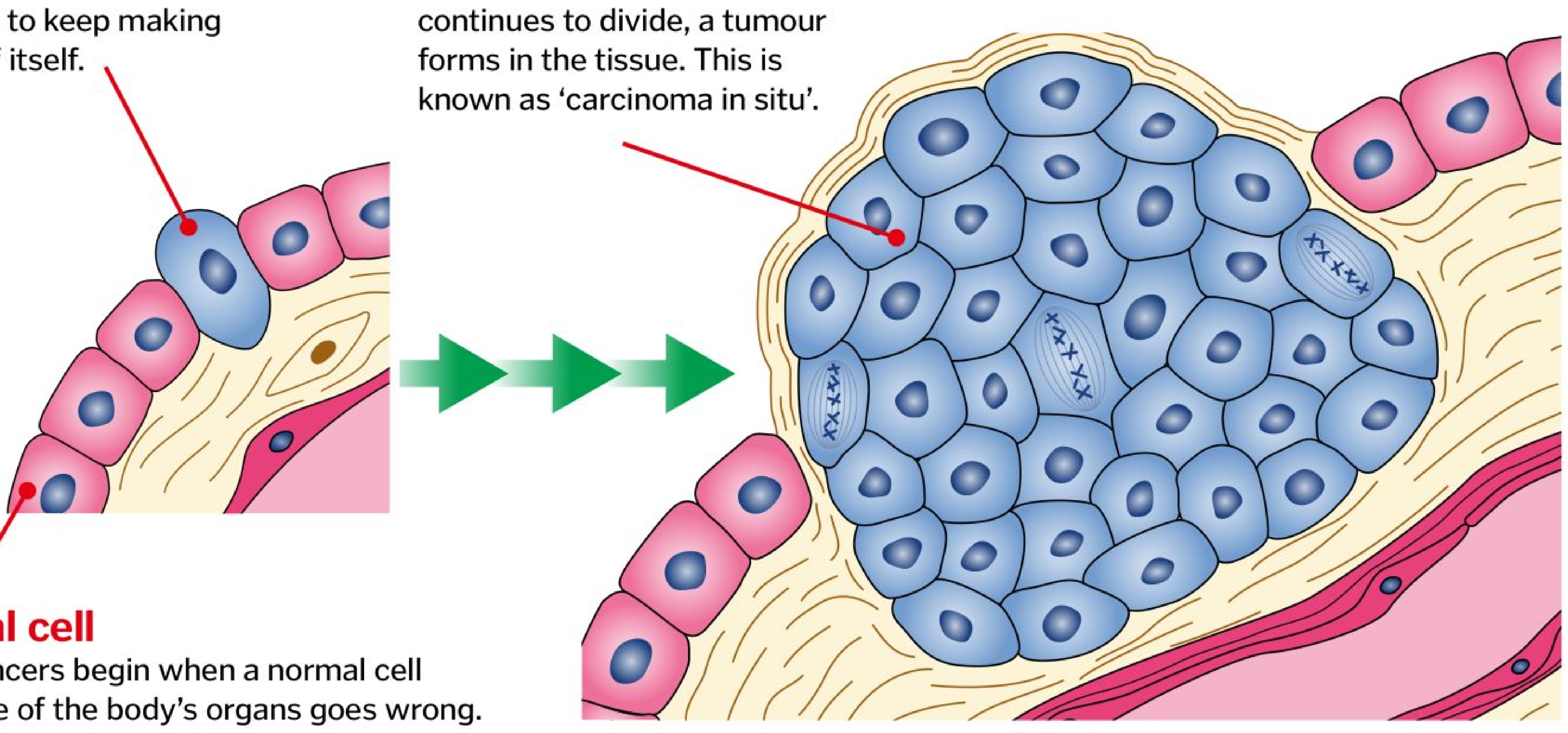
Cancer cells tend to have errors in genes known as 'oncogenes' or 'tumour suppressor genes'. Oncogenes are normally responsible for telling healthy cells to divide, helping with growth and wound repair, but mutations in cancer can cause them to become permanently switched on. Tumour suppressor genes, on the other hand, tell cells to stop dividing once growth or repair is completed, and errors in these genes can cause them to turn off. The result is that the damaged cells divide and divide and divide, piling up on top of each other to form a tumour.

With their safety systems switched off and nothing to tell them to stop, cancer cells keep making copies of themselves with more mistakes in their genetic code, and this leads to Darwinian evolution at a rapid speed. Just as if a wild animal has a beneficial genetic trait it will be more likely to reproduce, if a cancer cell has a beneficial trait it will be more likely to survive.

Cancer cells forget what they are supposed to be doing and gain new abilities, developing traits that allow them to hide from the immune system, survive on less oxygen, and even evade chemotherapy. But, most dangerous of all, they gain the ability to move through the body, spreading to distant places via the blood or lymphatic systems and making new tumours elsewhere. But the more we understand about how cancer works, the better we are becoming at treating it.

How cancer starts

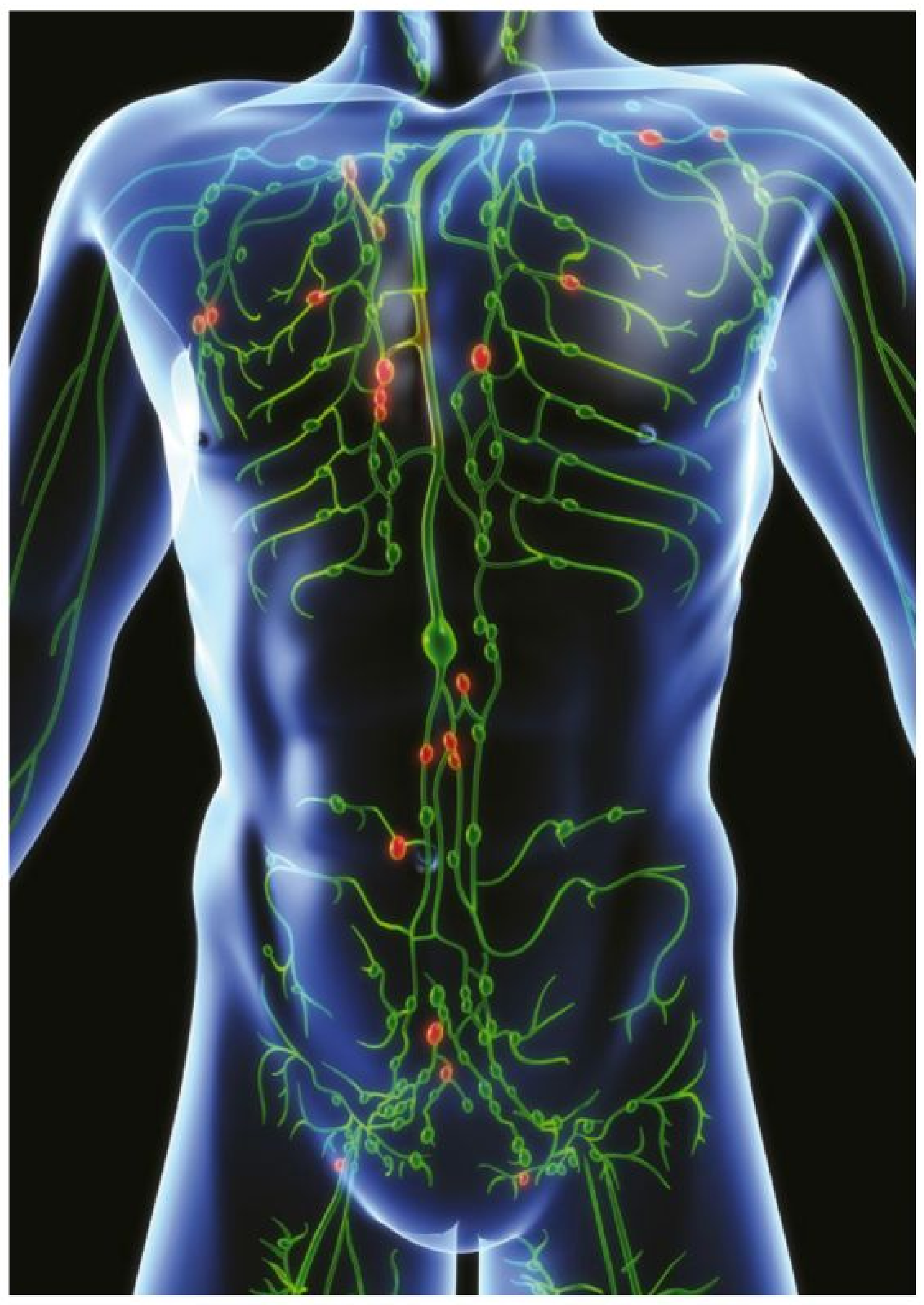
Cancer begins with a single mutated cell that divides and spreads



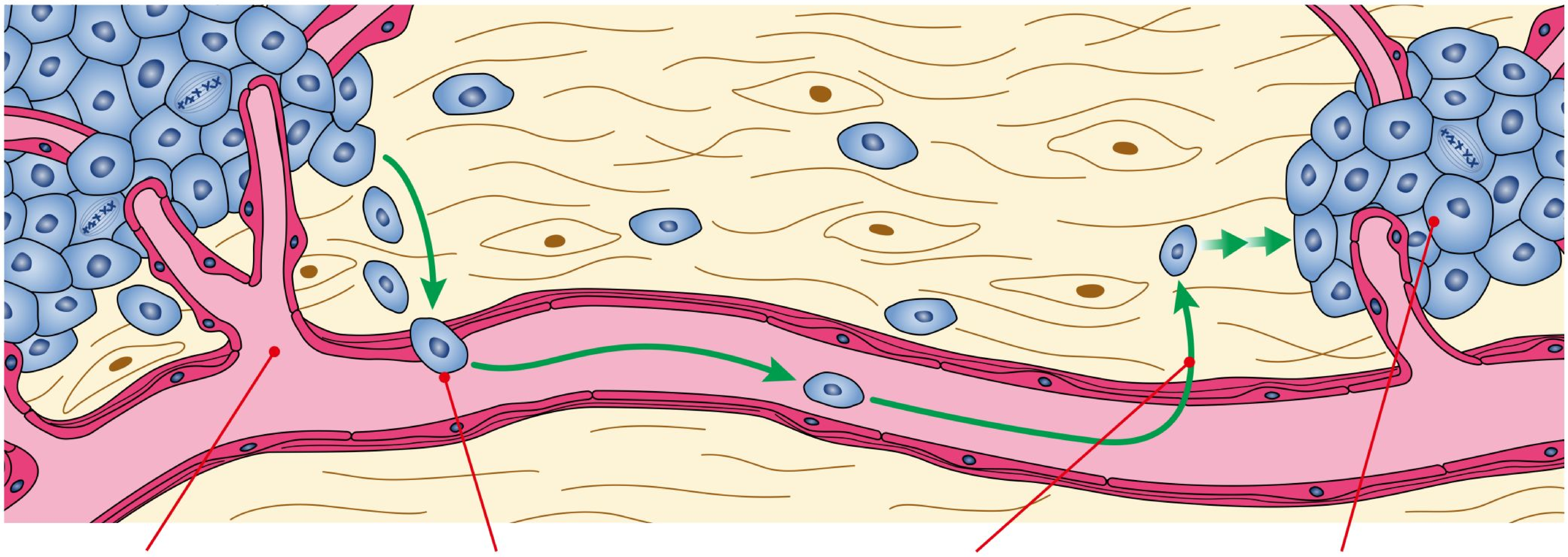
Cancer cell
Genetic errors inside the cell tell it to keep making copies of itself.

Tumour
As the abnormal cell continues to divide, a tumour forms in the tissue. This is known as 'carcinoma in situ'.

Normal cell
Most cancers begin when a normal cell lining one of the body's organs goes wrong.



Cancer cells can use the lymphatic system to spread around the body



Blood vessels
To keep growing the tumour needs a blood supply, so it encourages the formation of new blood vessels.

Distant spread
Cells start to break away from the main tumour, entering the lymphatic system and the blood vessels and spreading around the body.

Local spread
Eventually, the tumour starts to invade the local tissue, growing down into the connective tissue below.

Secondary tumour
Cancer cells become lodged in different tissues and continue growing, forming more tumours known as 'secondaries' or 'metastases'.

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Treating cancer

There are three major types of cancer treatment: surgery, radiotherapy and chemotherapy

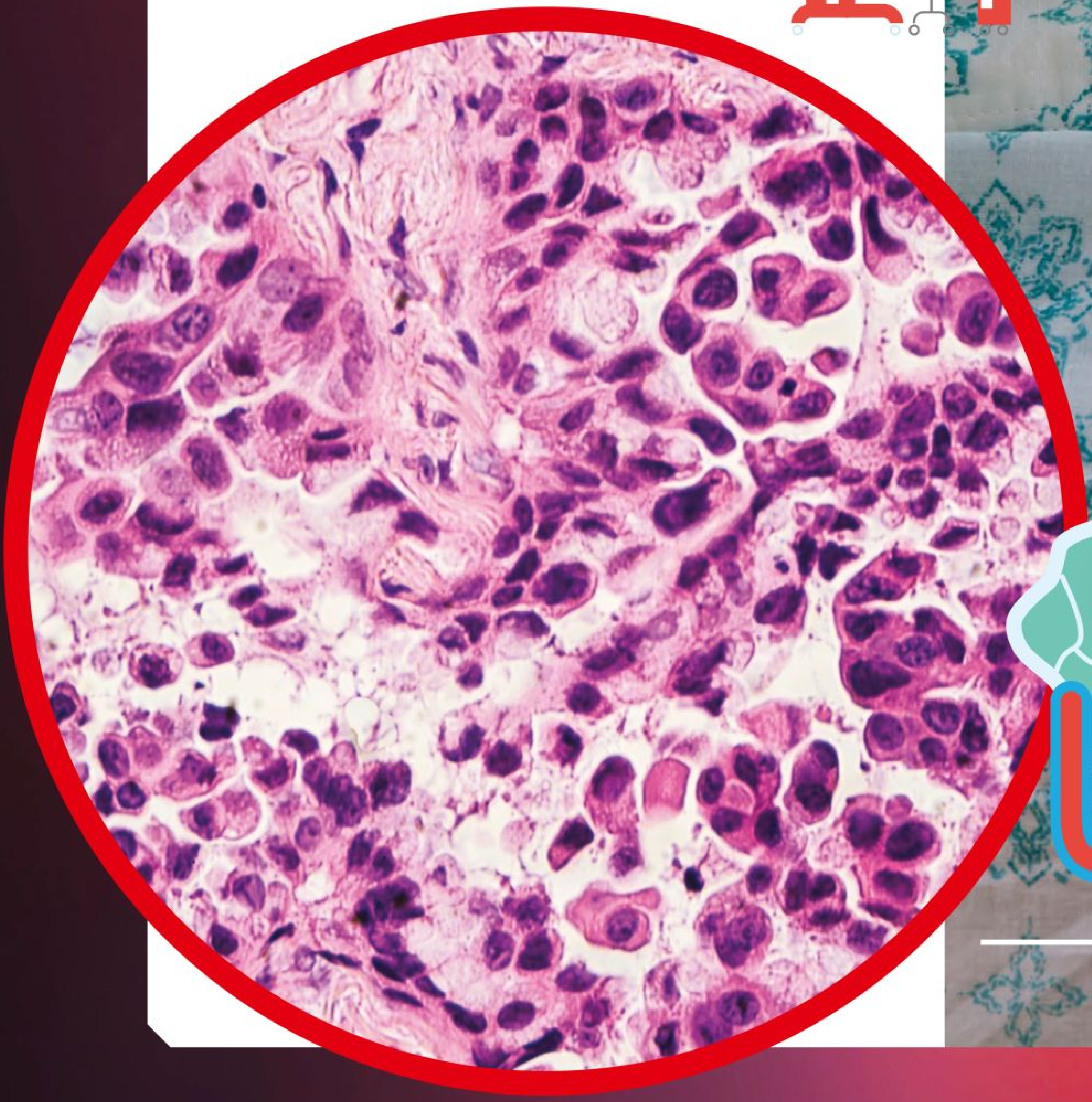
Chemotherapy

The first chemotherapy drug was developed using mustard gas, a chemical weapon used during WWI. Scientists had noticed that the poison killed the fast-dividing cells of the bone marrow, and so they adjusted the weapon to make nitrogen mustard, a treatment that could kill rapidly replicating cancer cells.

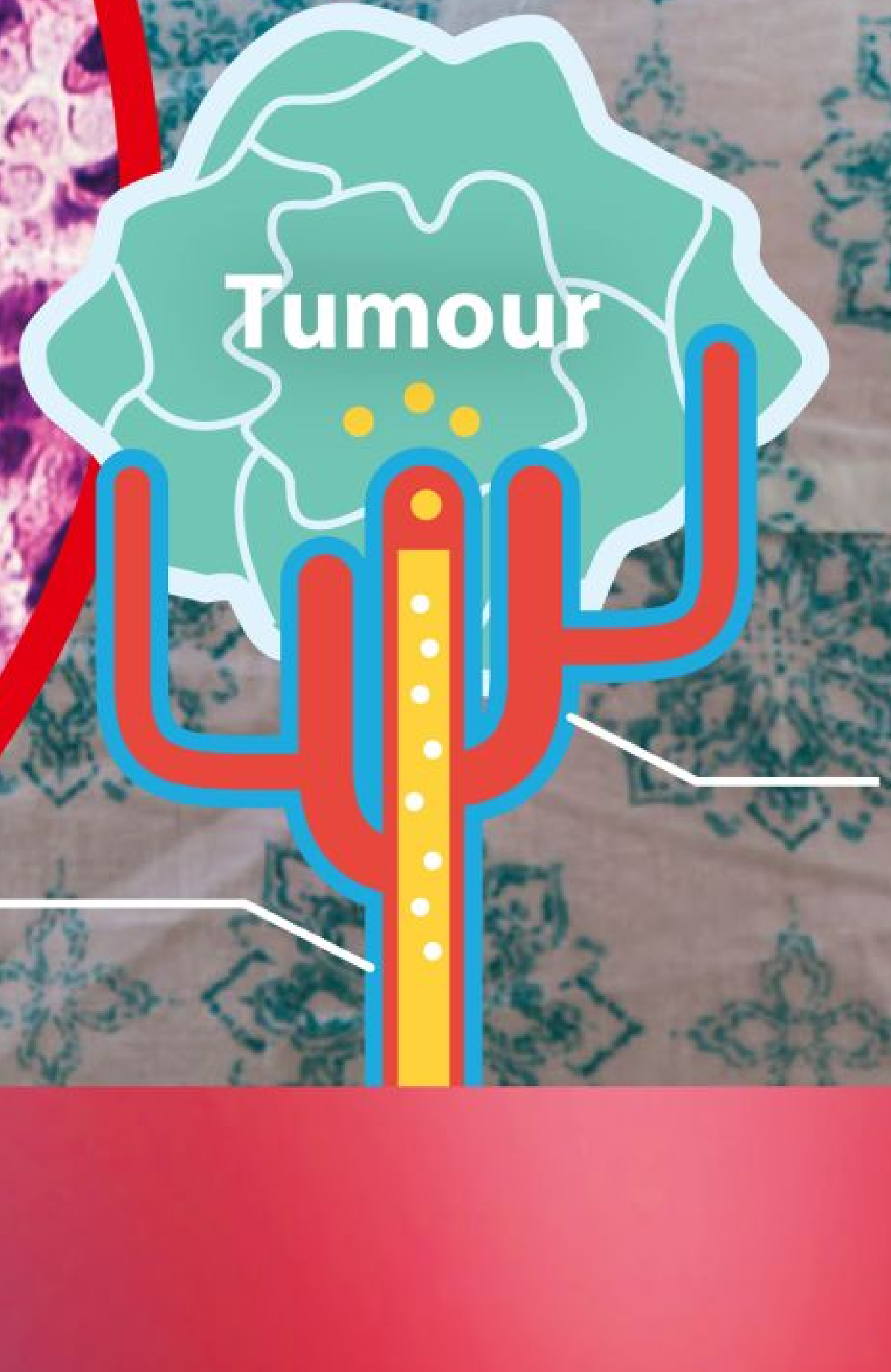
Nitrogen mustard belongs to a group of drugs known as alkylating agents, which work by adding chemical units called alkyl groups to DNA. These interfere with the double helix structure, causing the genetic code to break apart.

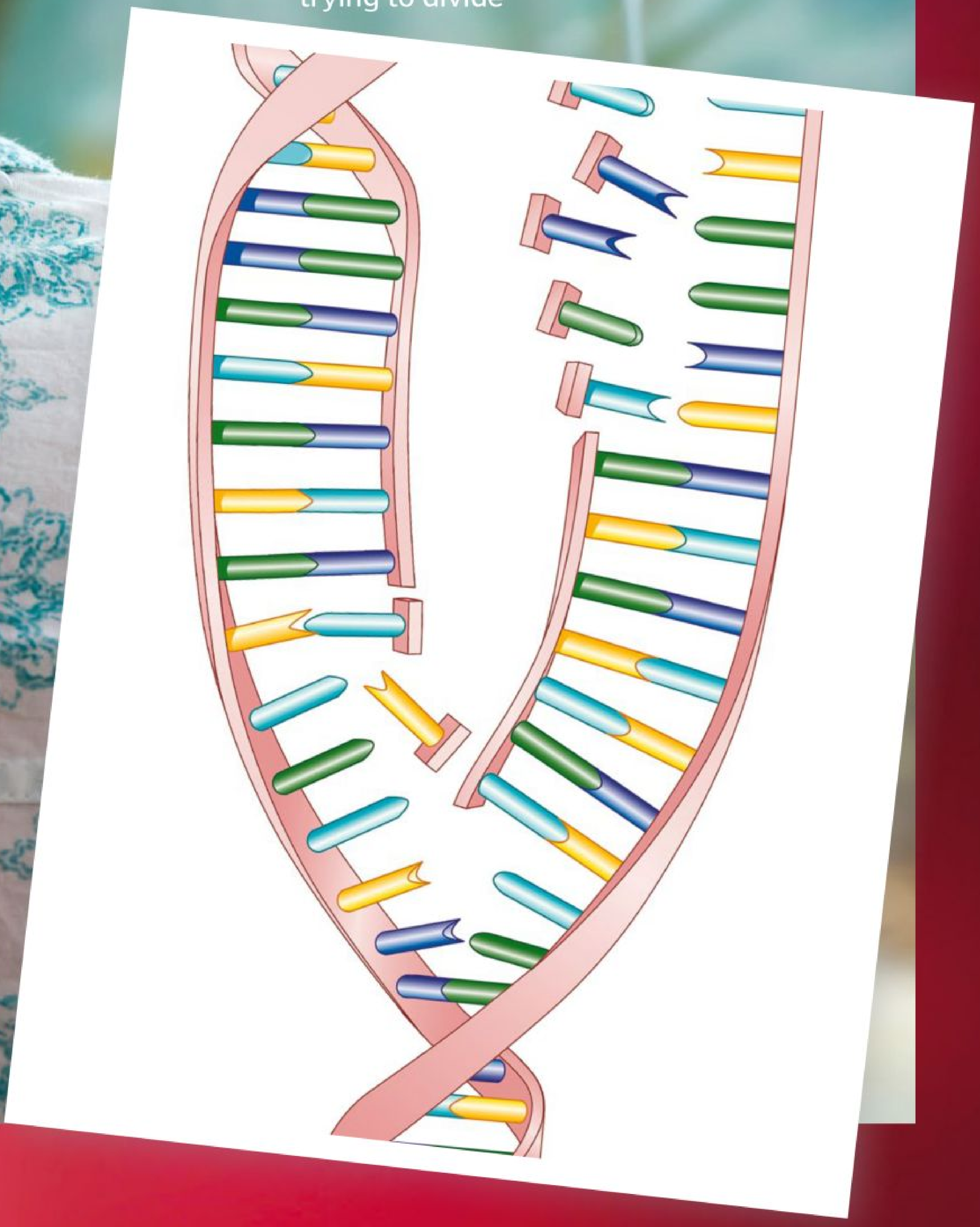
Other chemotherapies work in similar ways. Heavy metals cross-link DNA, preventing it from being read. Topoisomerase inhibitors stop the DNA helix from unwinding, and antimetabolites work by mimicking molecules involved in copying DNA, stopping the new sequence from being made. Anti-microtubule, or spindle poisons, stop cells from splitting apart, and cytotoxic antibiotics stick to the DNA helix, prevent unwinding, link different strands of DNA together or break DNA into fragments.

These treatments are particularly harmful to cells that are trying to make copies of themselves because they target DNA replication and cell division. This is good for catching fast-dividing cancer cells, but it isn't perfect. Cancer cells aren't always dividing, so some cells manage to escape the treatment, and lots of healthy cells also divide rapidly, too. Hair, skin and bone marrow (which makes blood cells) are all damaged by chemotherapy, leading to side-effects like hair loss, sickness and a weakened immune system.



Pathologists examine images like these to diagnose cancer. This lung tissue should be full of holes





Chemotherapies harm cells that are trying to divide

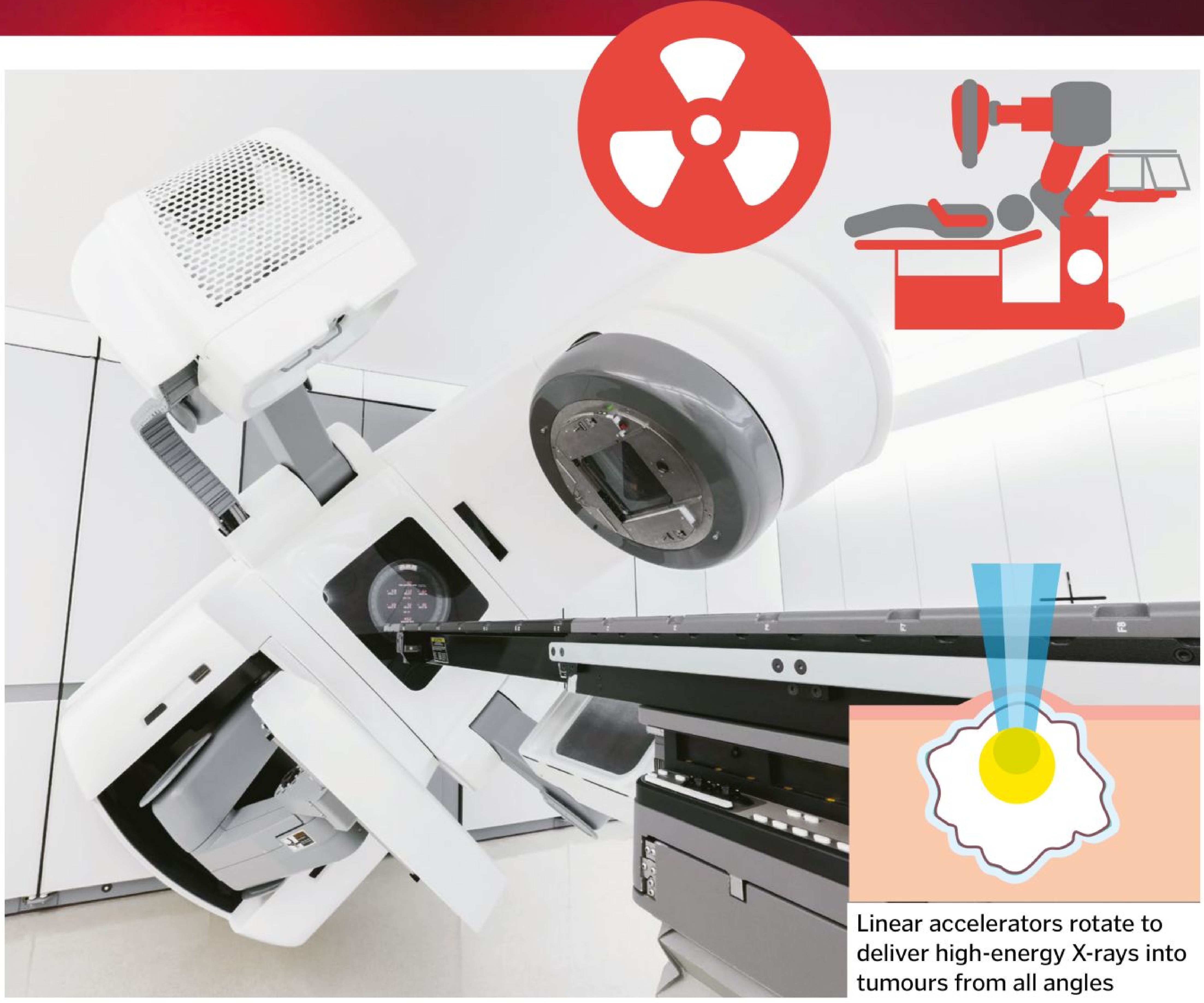
Radiotherapy

Radiotherapy was developed in the early 20th century and works by bombarding cancer cells with radiation. When the water molecules inside the cells are hit they split apart in a process called radiolysis. This makes highly reactive free radicals with an unpaired electron that attacks bonds belonging to other molecules, setting off a chain reaction that damages DNA.

Radiotherapy causes both strands of the DNA to break close together, a lesion known as a 'double-strand' break. This makes the helix unstable and it starts to unwind. Cells can repair a bit of this kind of damage, but the more radiation they receive, the more likely they are to die.

The most common way to deliver radiotherapy is by using a linear accelerator (LINAC). It uses microwaves to make electrons, which hit a heavy metal to make X-rays. CT or MRI scans are used to pinpoint the exact location of the tumour inside the body, and the X-rays are then shaped to fit the outline of the tumour. This is done by blocking part of the beam using sheets of metal known as a multileaf collimator.

X-rays go all the way through the body, so the machine rotates to deliver beams from all angles, giving the maximum dose where the beams cross over at the site of the tumour, minimising the amount of radiation received by the surrounding healthy tissue.



Linear accelerators rotate to deliver high-energy X-rays into tumours from all angles

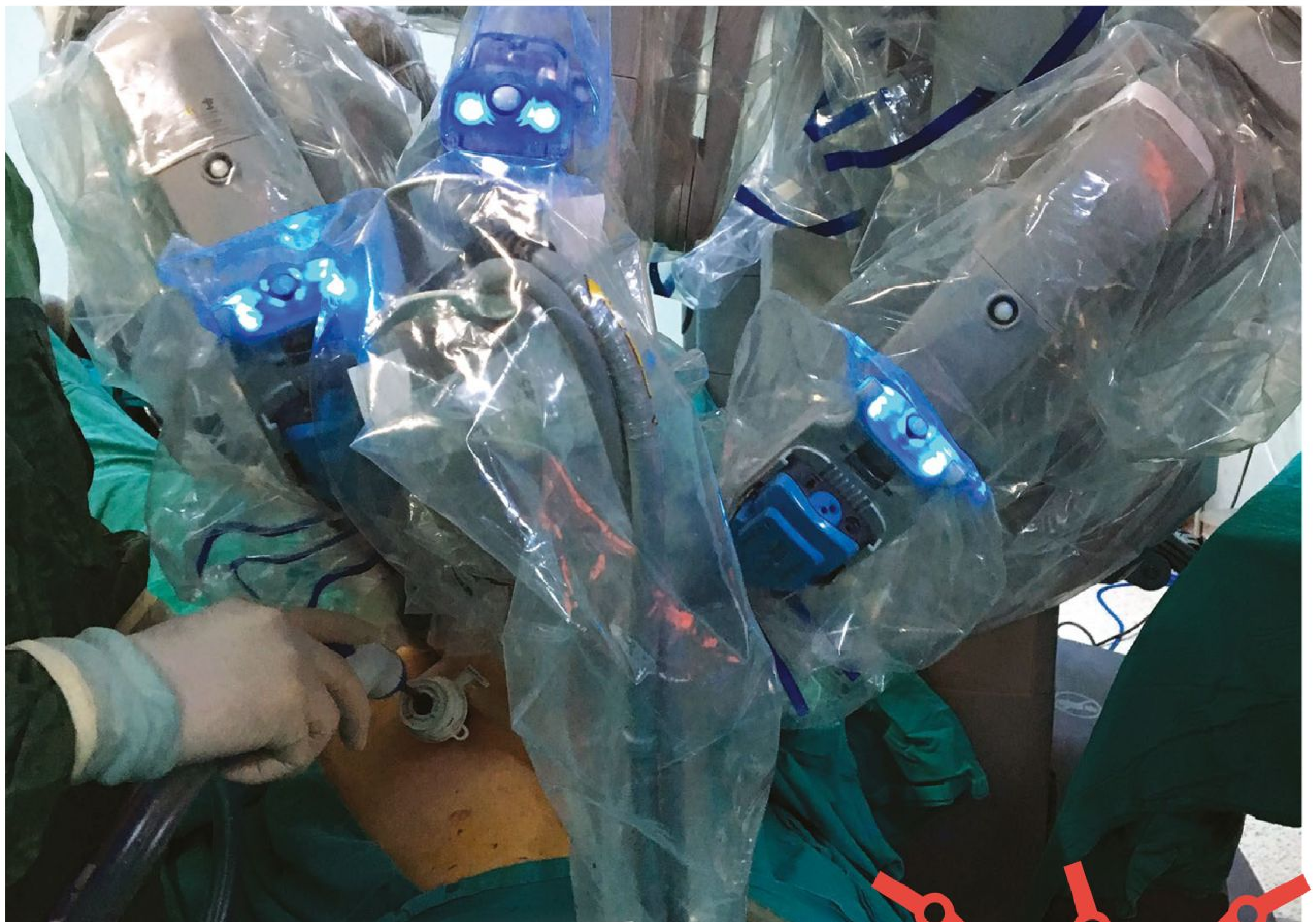
Surgery

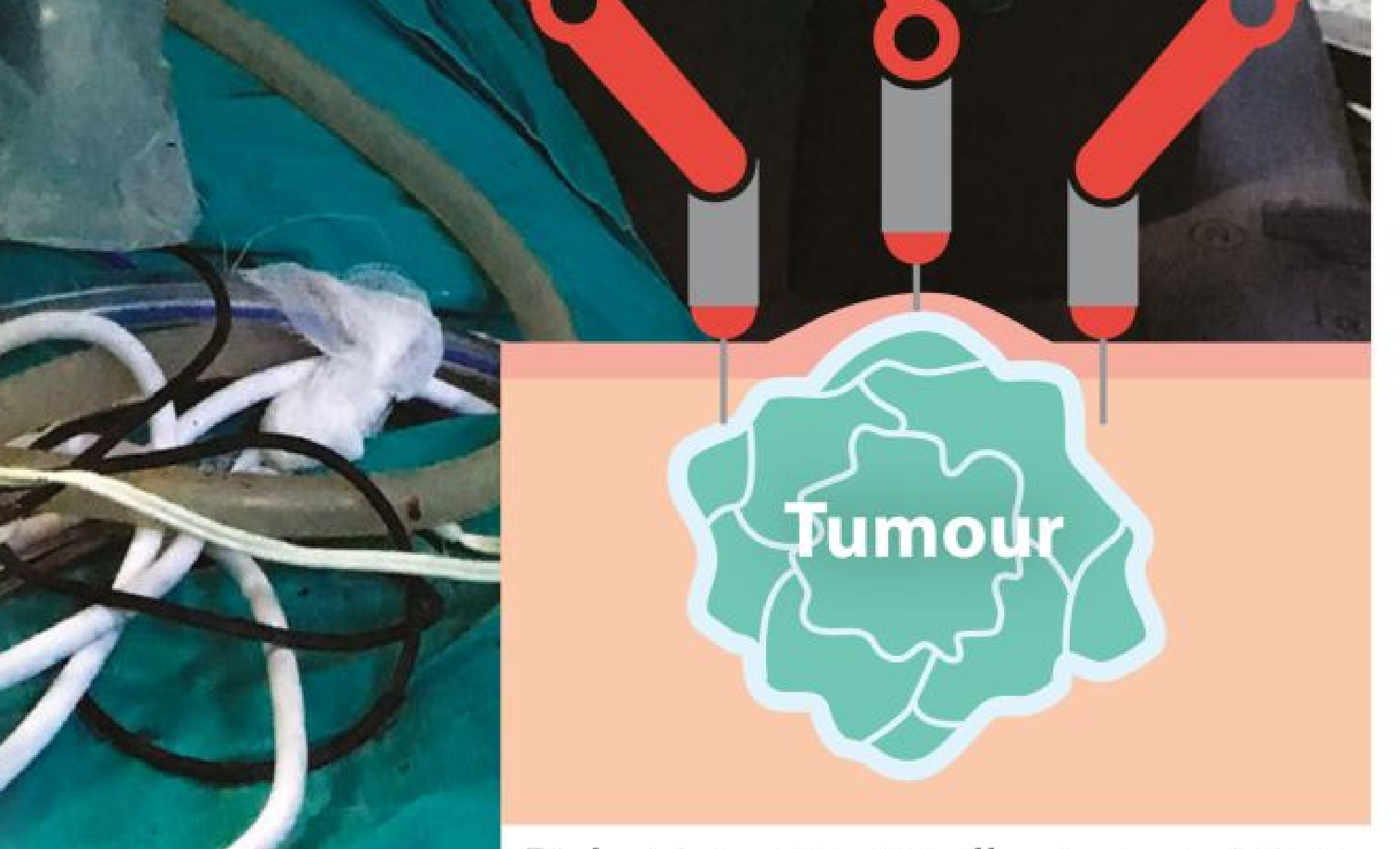
Surgery is one of the oldest and most effective cancer treatments. If the cancer hasn't spread, surgeons take out the whole tumour and some of the surrounding area in case there are any cells that can't be seen. Nearby lymph nodes may also be removed as these are often the first place a cancer will spread to.

If the whole tumour cannot be removed, surgery can also be used for 'debulking', where as much of the tumour is removed as possible so the rest can be treated with chemotherapy or radiotherapy. Surgery can also be palliative, relieving symptoms when cancer cannot be cured.

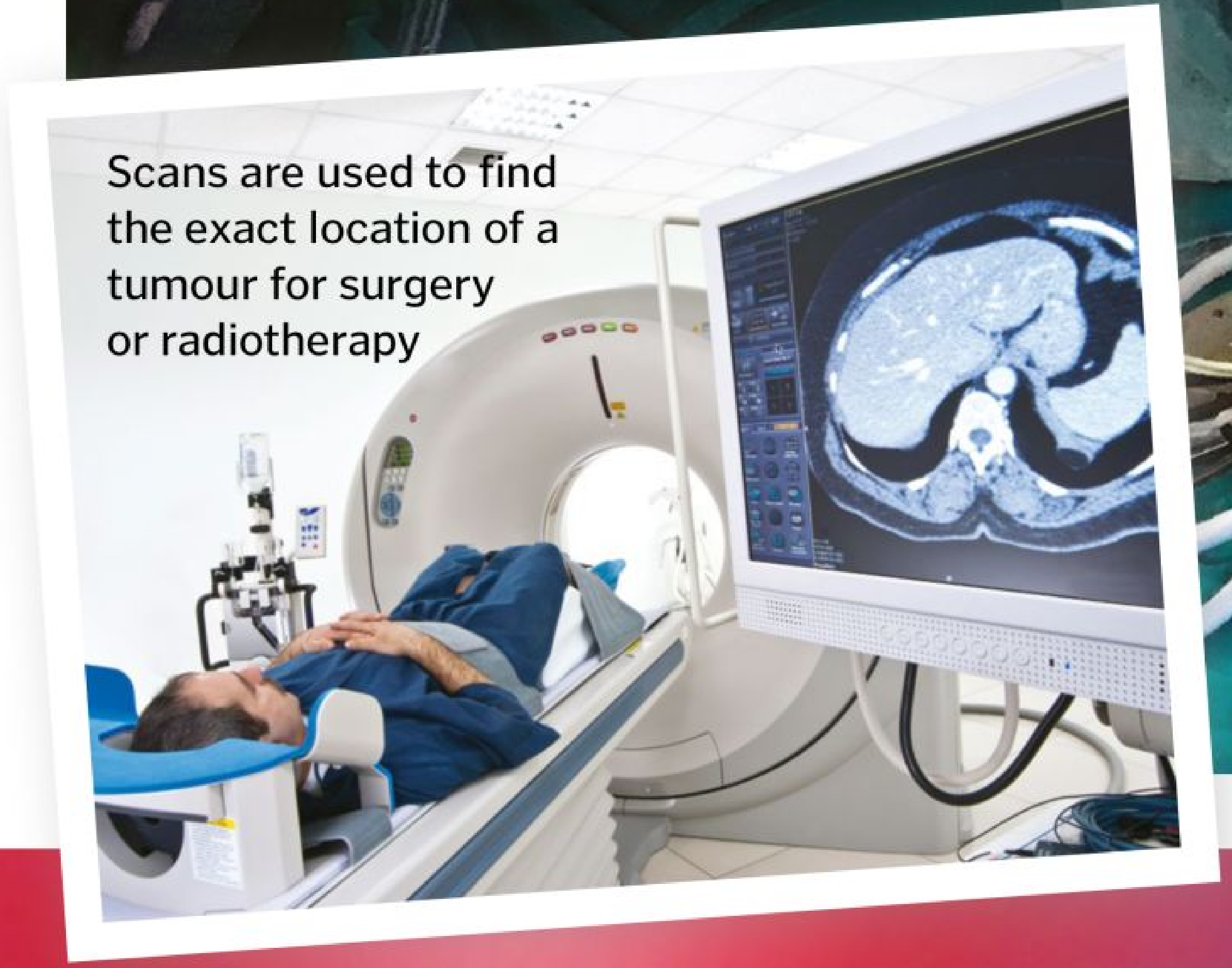
Not all lumps are tumours and not all tumours are cancer, so surgery is often used for cancer diagnosis, too. A small sample of tissue, known as a biopsy, is removed and either frozen solid or embedded in wax so that it can be thinly sliced. These slices are stained so that a pathologist can examine the structure of the cells and tissue.

Cancer cells look different under a microscope, creating disorganised structures in normally orderly tissues, and they also display specific molecular or genetic markers that single them out. These not only help with a cancer diagnosis but can also be used to determine the type of cancer, how advanced it is and the best form of treatment to use against it.





Robotic surgery allows precision operations to be performed



Scans are used to find the exact location of a tumour for surgery or radiotherapy

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The future of cancer treatment

The more we learn about cancer, the better we are able to target its weaknesses

In the UK, overall cancer survival is now at 50 per cent, and ten-year survival for testicular cancer has reached an impressive 98 per cent. But there's still a way to go. There are hundreds of different types of cancer, and even patients with the same cancer type have subtle differences in their tumours that change their response to treatment. Cancers can become resistant to chemotherapy and radiotherapy, and many treatments also harm healthy cells, causing side-effects that limit their use.

Until recently, most cancer treatments have focused on one thing: cell division. Both radiotherapy and chemotherapy hit rapidly dividing cells, damaging their DNA as they try to replicate, causing them to die. But cancer has lots of other weaknesses and scientists are attacking from all angles, using the latest tech to reveal their genetic and molecular differences.

One tactic is to cut cancer's fuel lines. As tumours grow and cells pile on top of one another, oxygen levels drop and the cancer cells encourage new blood vessel cells to break down tissue and migrate in. Blocking this process could stop tumour growth in its tracks.

Another option is to use the immune system, helping our own cells to see cancer cells and destroy them. Techniques being trialled include using molecules to block the interaction between cancer cells and immune cells, preventing the tumour from switching the immune system off, and genetically engineering immune cells to supercharge their ability to seek and destroy cancer cells.

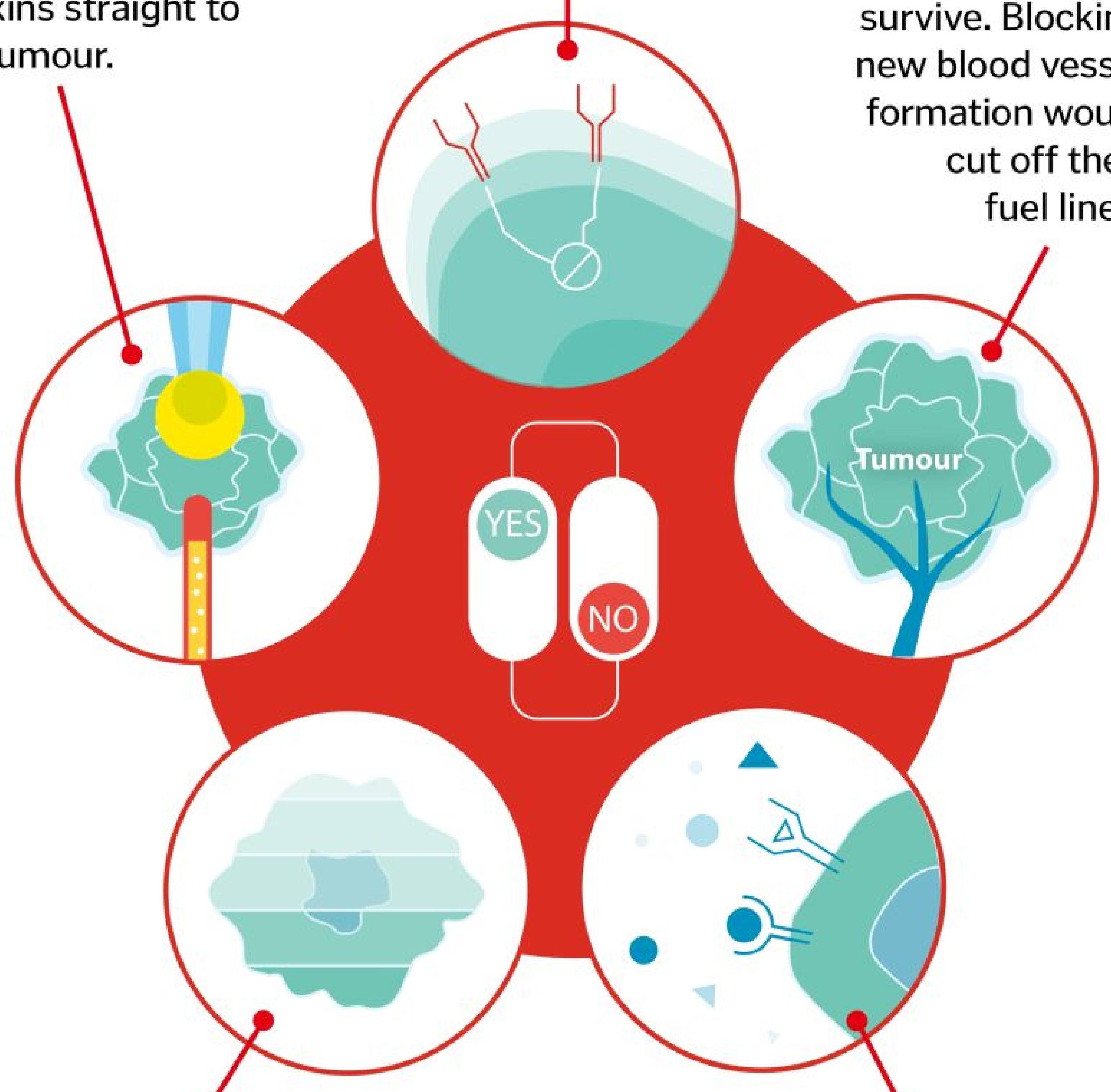
Immune molecules called antibodies are also being transformed into highly targeted cancer treatments that should leave healthy cells unharmed. They can be made to stick specifically to a single molecule, blocking the chemical signals that tumours need to survive or attaching directly to the cancer cells. They can even be linked to chemotherapy or radiotherapy molecules, delivering a double hit of toxin and immune attack.

Researchers are also working on genetically modifying viruses to infect and kill cancer cells, delivering drugs into cancer cells using nanoparticles and designing small molecules to interfere with the crucial molecular machinery that cancer cells use to survive.

It's very unlikely that there will ever be a single cancer cure, but the more we learn, the more targeted treatments will become, killing cancer cells more effectively and leaving healthy cells unharmed.

Targeting cancer's weaknesses

Modern techniques are zeroing in on the molecules and genetics that make cancer cells vulnerable



Molecular tags

Cancer cell molecules look different. Targeting these could deliver toxins straight to a tumour.

Growth signals

Cancer cells receive signals that tell them to keep growing. Blocking these could halt the process.

Blood supply

Cancer cells need a blood supply to survive. Blocking new blood vessel formation would cut off their fuel lines.

Self-destruction

Cancer cells don't die even though they are faulty. Targeted therapies could switch self-destruct systems on.

Hormones

Some cancer cells are driven by hormones. Stopping their production could slow growth.

Trawling cancer genetics

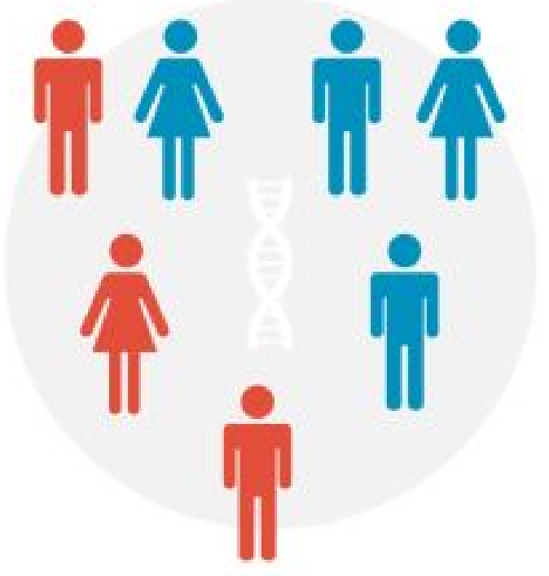
Cancers have distinctive mistakes in their genetic code that could reveal weaknesses.

Pathology

Cancer cells can be tested for the presence of molecules that single them out as defective.

Custom treatment

Individual patients could be matched to the treatments most likely to work for their unique tumour.



Customising cancer treatment

The Human Genome Project unravelled the human genetic code in 2003. This epic sequencing mission detailed every single letter of our DNA, revealing for the first time the complete recipe book for a human body. Cancer cells read from the same recipe book as healthy cells, just with words blotted out, pages stuck together and sentences scrambled. By understanding how the recipe book is supposed to be put together, scientists are now better able to identify why and how cancer cells have got it so badly wrong.

Every person is slightly different and their cancer cells start with a slightly different set of instructions, and as the disease progresses, different tumours adapt in different ways. Two women might both have breast cancer, but although there are patterns of similarity, the genetics inside their cancer cells won't be exactly the same, so they don't always respond in the same way to treatment. In the future, people will be tested to reveal the targeted treatments that will work best for them.

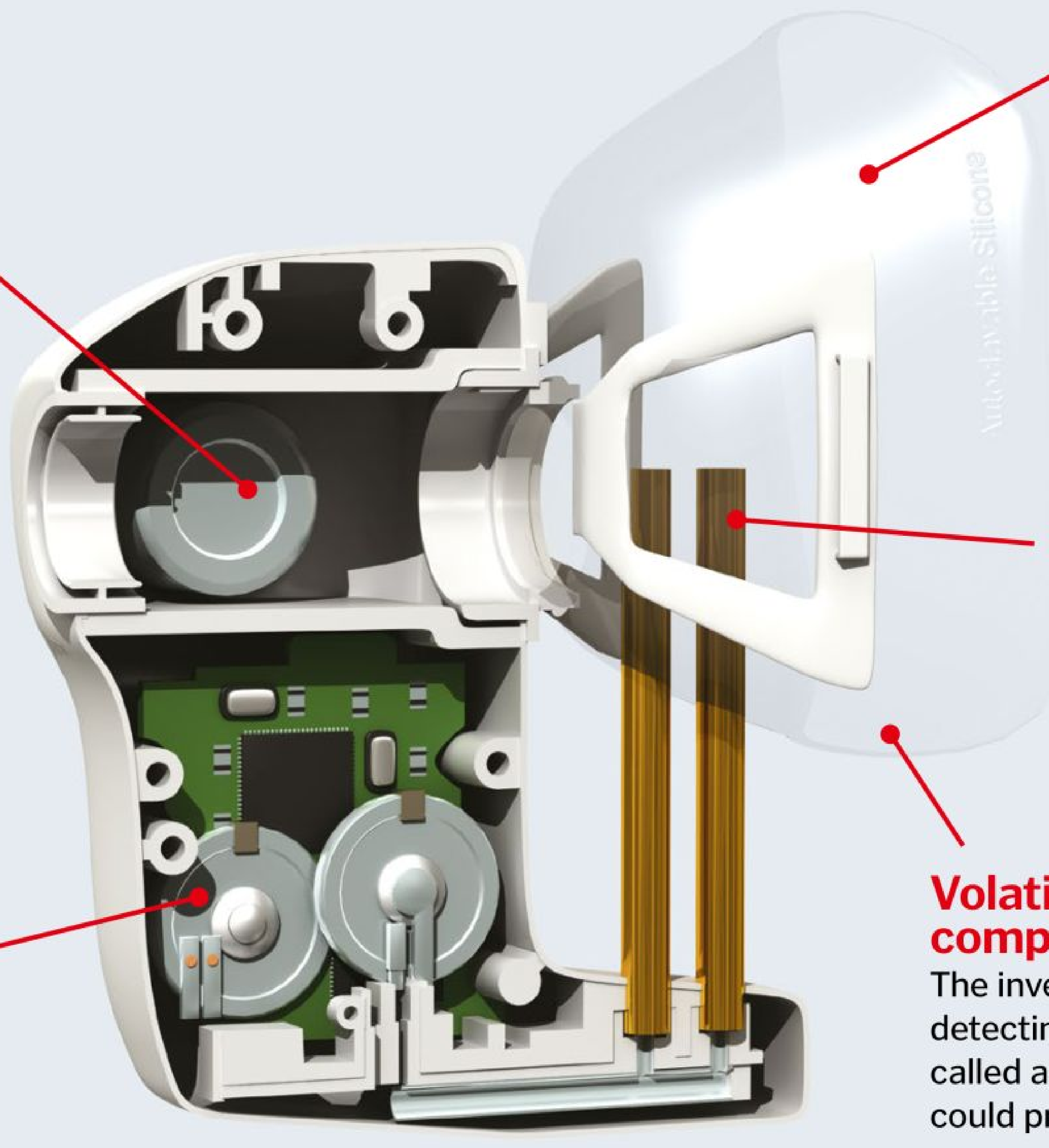
Different cancers carry different mistakes and respond differently to treatment

Catching cancer early

The sooner cancer is detected, the easier it is to treat. There are already three screening programmes in operation in the UK to detect bowel cancer, breast cancer and cervical cancer, but in the future things could become a whole lot simpler. Research into 'biomarkers' is searching for molecular signals that could reveal cancer in a simple blood, urine or even breath test.

Biomarkers are molecular signatures unique to different types of cells. Cancer cells differ from normal cells in ways that can already be detected using biopsies of tumour tissue, but researchers think that these differences might also make their way into body fluids, allowing them to be picked up with a simple test. Biomarkers might be able to reveal clues about the best treatment to use, whether the tumour is becoming resistant to current drugs and whether cancer has returned.

> "One tactic is to cut cancer's fuel lines"



Sensors
Sensors detect carbon dioxide and pressure for breath monitoring.

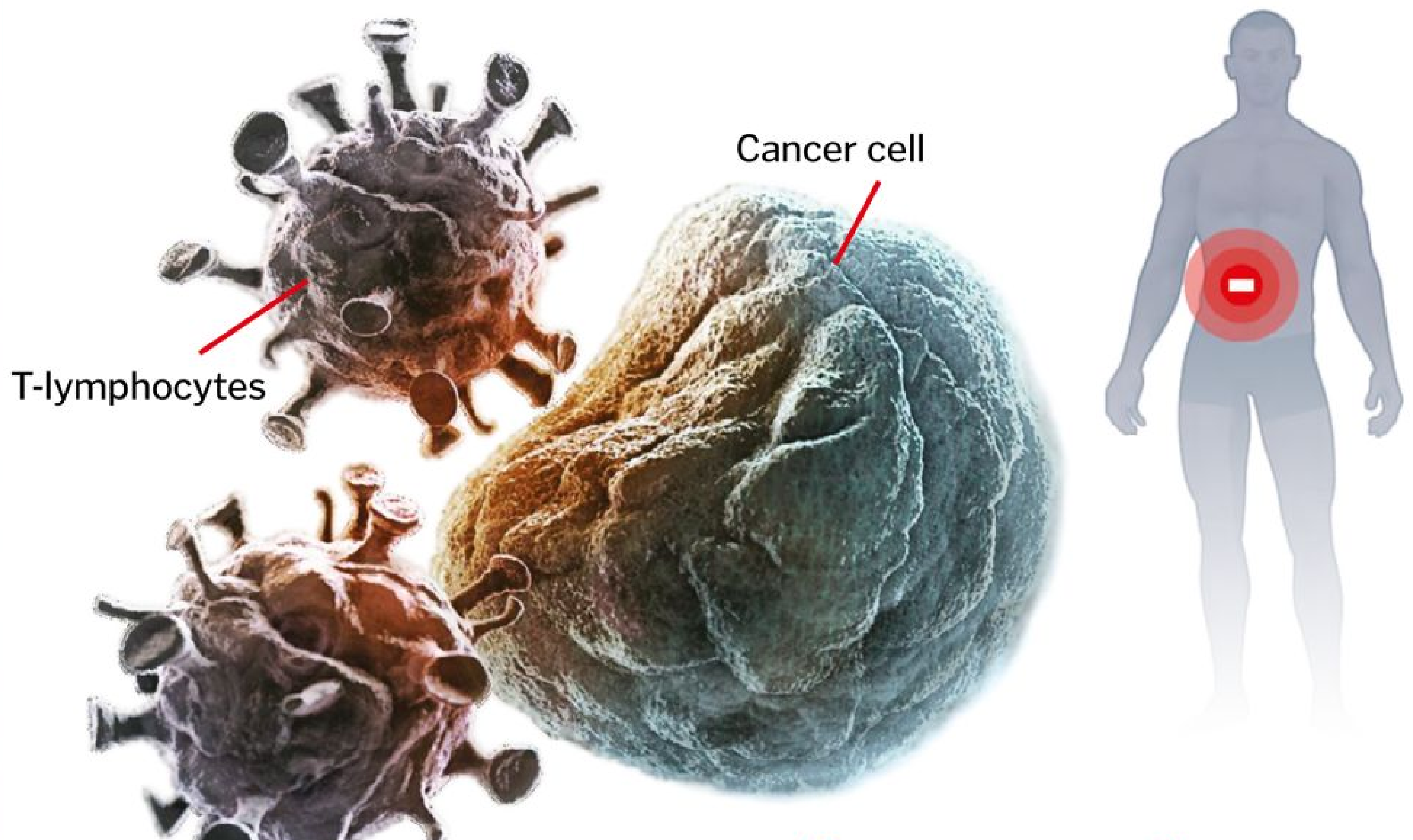
Facemask
Single-use masks with a filter are used to blow air into the device.

Sorbent tubes
The breath is separated into fractions and stored in two pairs of tubes that can be analysed in the lab.

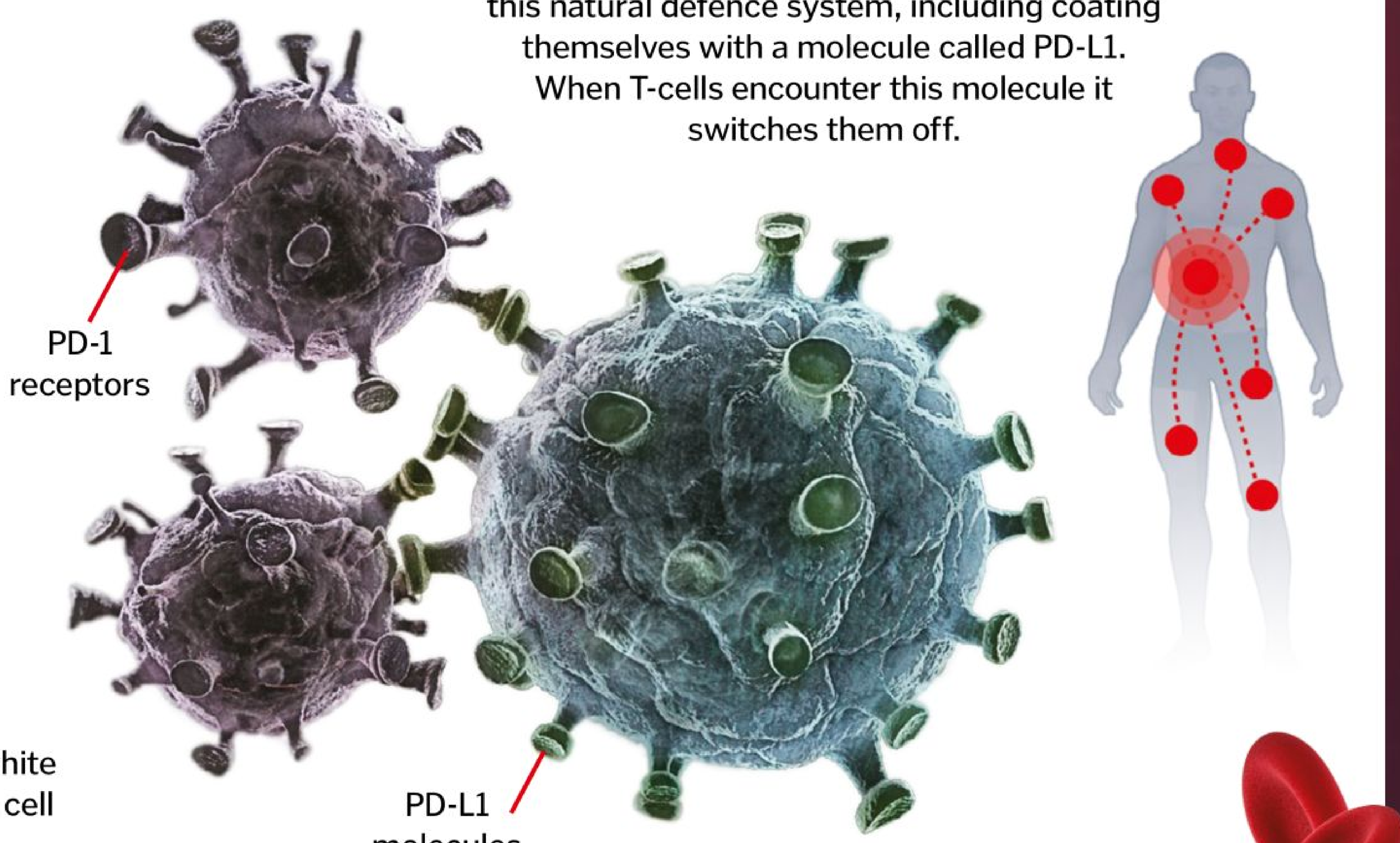
LuCID clinical trial
The device is currently being trialled to find out whether it is effective for lung cancer diagnosis.

Volatile organic compounds
The inventors hope that detecting traces of chemicals called aldehydes and ketones could predict lung cancer.

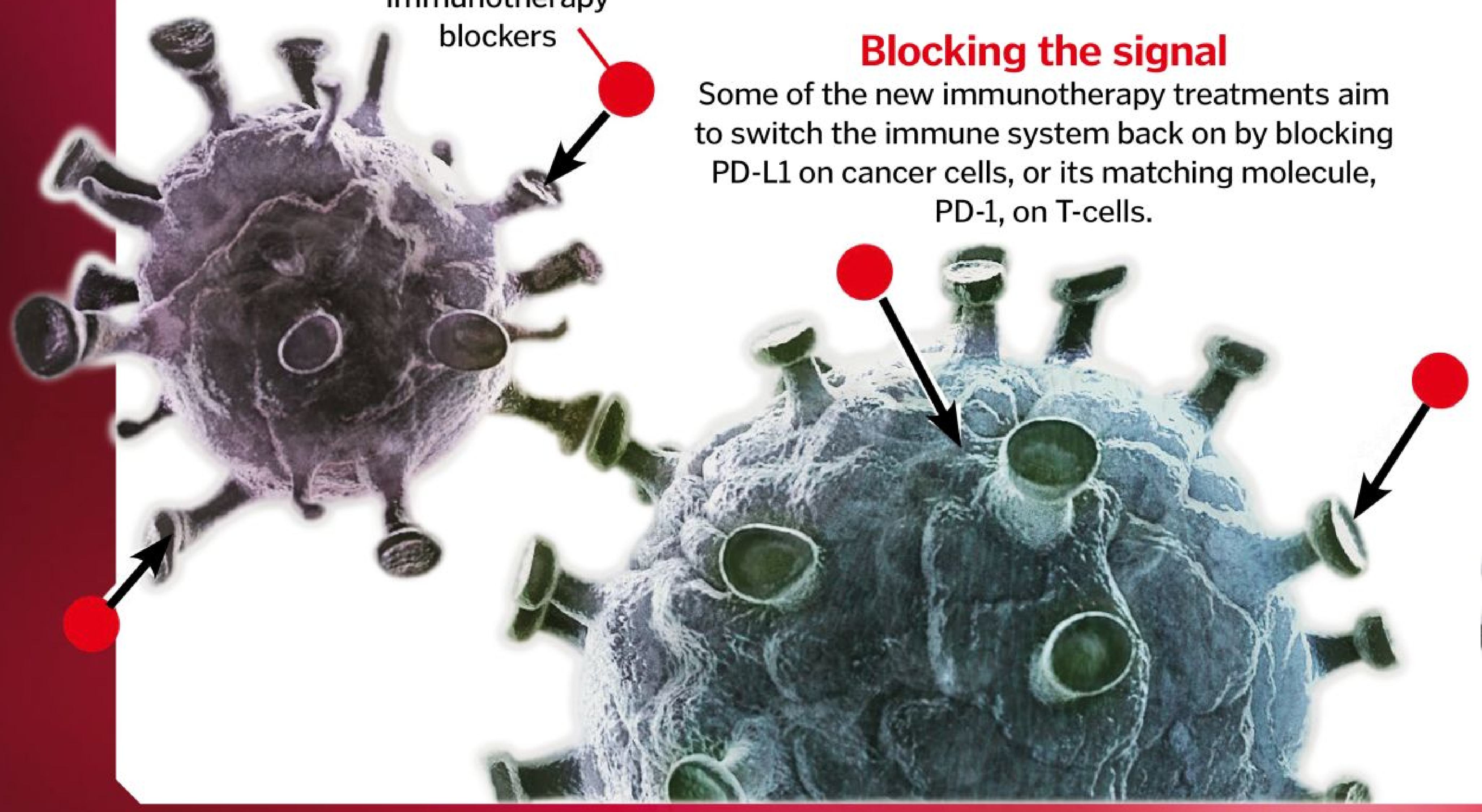
Strengthening your immune army



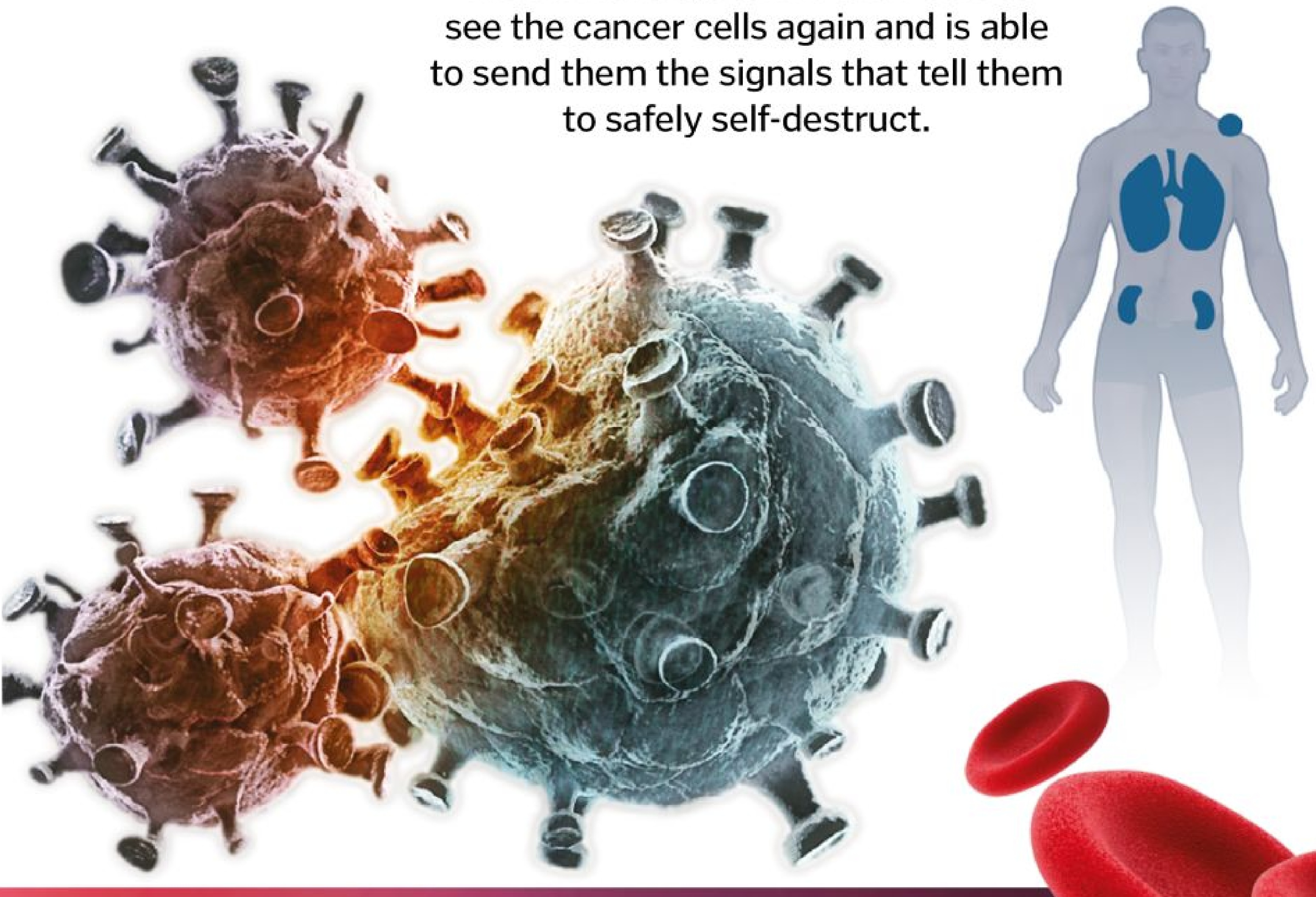
Cancer prevention
Your body is equipped with an army of 'killer' T-cells: white blood cells that patrol the body looking for trouble. If a cell starts to go wrong, these cells come in and kill it.



Subterfuge
Cancer cells develop different ways to evade this natural defence system, including coating themselves with a molecule called PD-L1. When T-cells encounter this molecule it switches them off.



Blocking the signal
Some of the new immunotherapy treatments aim to switch the immune system back on by blocking PD-L1 on cancer cells, or its matching molecule, PD-1, on T-cells.



Killing cancer
The immune system is then able to see the cancer cells again and is able to send them the signals that tell them to safely self-destruct.

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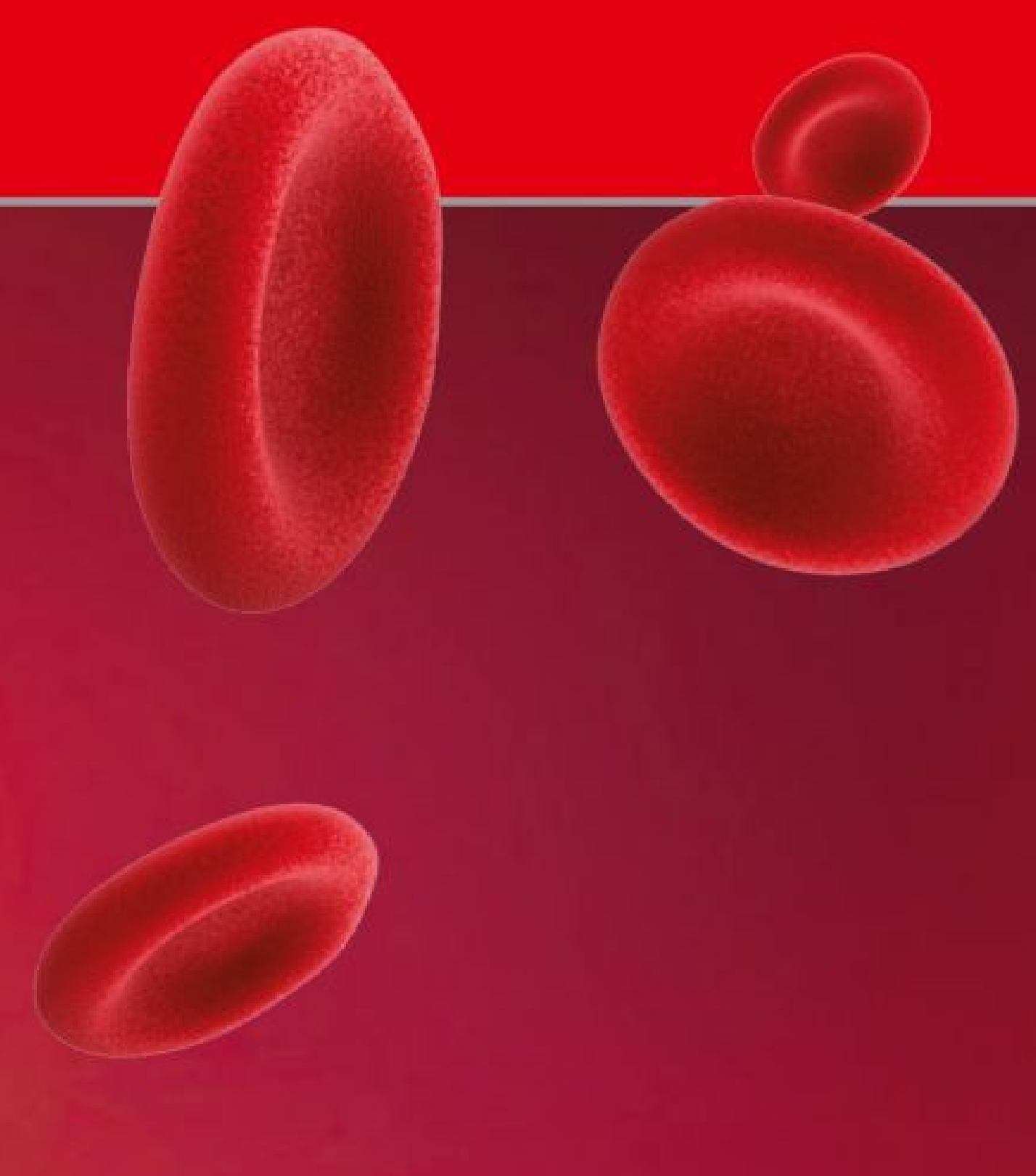


Expert opinion

We spoke to an immunologist and a research nurse about the future of cancer treatment

The immunologist

***Dr Edd James** is an associate professor in cancer immunology at the University of Southampton, one of the country's leading centres for immunotherapy research*

Could you tell us a bit about your research? What are you trying to find out?
The immune system, in particular the 'infantry' known as killer T-cells, are able to detect cancer cells through examining small protein fragments presented on larger proteins called MHC at the surface of cells. Almost all cells have these MHC molecules and they act as a way to understand what is going on in the cell at that moment. Despite these molecules, cancer cells are able to 'hide in plain sight' from the killer T-cells. We are investigating how they do this and how to either reverse this process or re-educate the killer T-cells to be able to 'see' the cancer cells through changing what the MHC molecules show them.

Why can't the immune system just kill cancer cells on its own?
In many instances, the immune system does kill cancer cells at an early stage of development without us knowing about it. However, cancer cells 'evolve' to hide themselves to prevent the immune system from finding and attacking them. In addition, the cancer cells are able to promote an environment that suppresses the immune response, thus preventing it from working properly.

How does immunotherapy help?
Immunotherapy works in many ways, but there are two main methods by which it can help. The first is to target molecules that the cancer cells have on the cell surface using proteins called antibodies. These are specific for particular molecules and once bound to the target molecules serve to highlight the targeted cancer cells to the immune system. This allows them to be identified, attacked and destroyed.

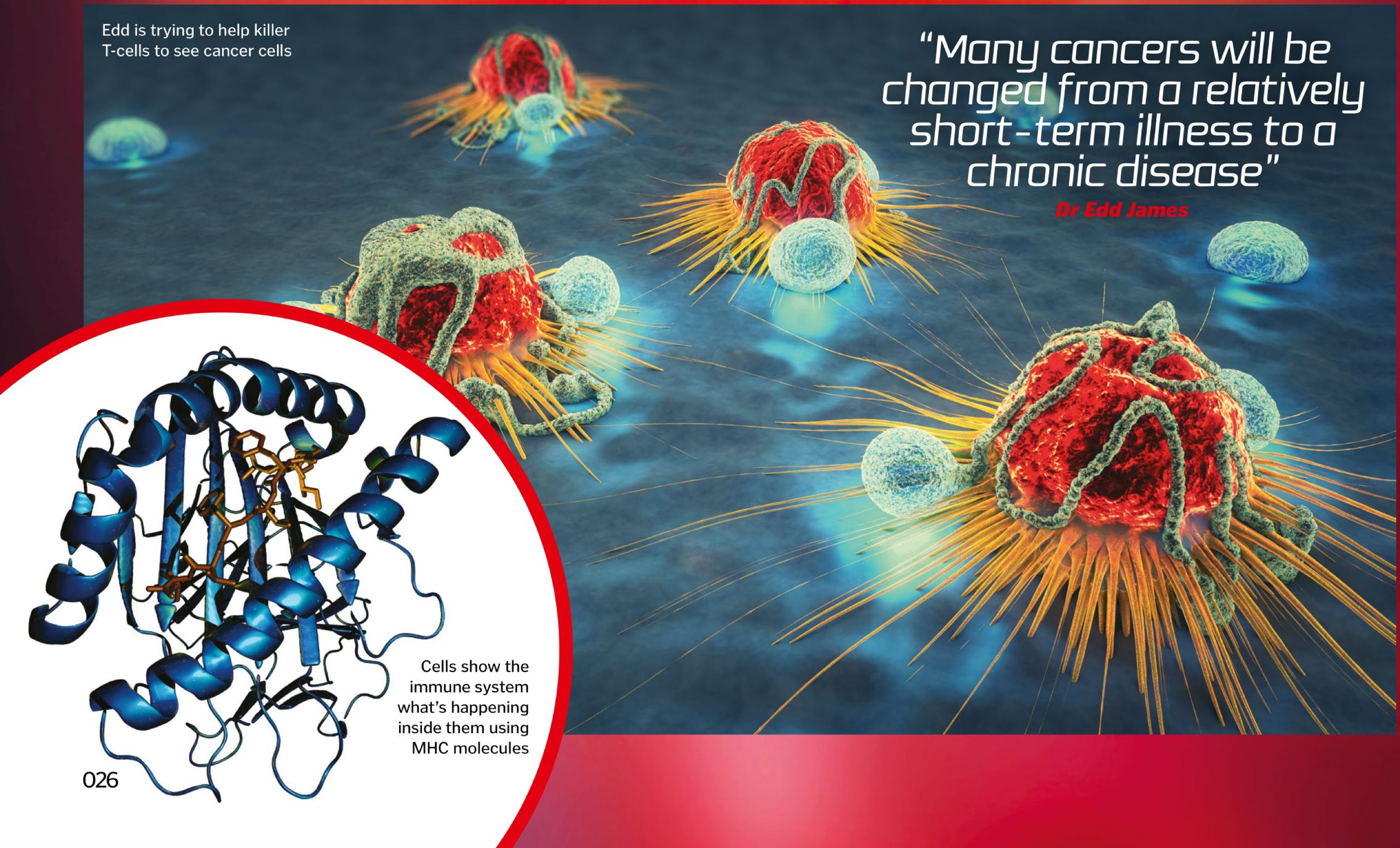
The second method is to target the killer T-cells themselves. Cancer cells are able to put the brakes on the killer T-cells to prevent them working properly. This occurs because the cancer cells deliver a negative, inhibitory signal to the killer T-cells through interaction. These signals are produced through a number of different molecules that can be blocked using antibodies. Blocking these interactions prevents the negative signals and allows the killer T-cells to work normally and kill the cancer cells.

What needs to be done next to make immunotherapy better?
Currently the therapies that are used are relatively blunt tools and aren't effective in many people. We need to understand how the cancer blocks the immune system in greater detail. This will give us a better appreciation of the processes involved in allowing cancer cells to evade the immune system and also allow us to identify new molecules to target.

There are many new investigations looking to combine current immunotherapies to improve their success. In trials these are working much better. However, a major downside of many of these combinations is an increase in side- effects that needs to be addressed.

Do you think we will ever cure cancer?
There is likely to be an effective cure for a number of cancers in the future. Our greater understanding of the molecular aspects of a cancer, and how to utilise the immune system more effectively to kill the cancer, will greatly increase possible treatments and improve their efficacy. This will allow a much more personalised approach to treatment based on the molecular characteristics of the cancer.

These advances will mean that many cancers will be changed from a relatively short-term illness to a chronic disease, where patients are treated as and when cancer arises. This will increase cancer-free survival, effectively enabling many people to live a normal lifespan.



Edd is trying to help killer T-cells to see cancer cells

> "Many cancers will be changed from a relatively short-term illness to a chronic disease"
> **Dr Edd James**

Cells show the immune system what's happening inside them using MHC molecules

The research nurse

***Jac Samuel** is a CRUK senior research nurse. She leads a team of research nurses delivering clinical trials testing brand new cancer treatments for the first time*

Could you explain a bit about what research nursing is?
Research nursing is a really interesting career pathway, which most nurses when they qualify don't even consider. You think you're going to work on a ward, and you obviously go into nursing because you want to look after people and help them. Research nursing is interesting because you're working with new treatments that are not licensed.

It's a process of gathering data, which is then analysed to see whether or not this new treatment is comparably better than what we've currently got. It might be that it works better, or it might be that it doesn't work any better but it doesn't have such bad side-effects. Or maybe, instead of giving it via somebody's vein, they might be able to take it in the form of a tablet.

As a research nurse you're delivering those treatments to patients. We don't know how well it works, so we're conducting an investigation. What we're aiming for is really good quality data that can be analysed to prove how well something is working.

Why do treatments have to go through trials?
You can't just give something from a lab because you don't know how it works. Even if it's worked in an animal model, you don't know how it's going to work in a human. Everything has to be tested to make sure it's safe. Otherwise you could have some company saying, 'Hey, we think this really works and it's a cure, and we're going to charge you £50,000 for it' but there would be no evidence for that.

The whole point of research is that it's evidence-based. The laboratories will create the treatment, and they will test it in a cell line and in an animal model, but it's very different to how it might work in a human.

What changes have you seen in cancer treatment?
I've been nursing for a long time now, but even in the last five years actually it has really changed. Scientists have so much more understanding now of the intricacies of cells. Before, there used to be a blanket term for several different sorts of cancer. It's so much more nuanced now, and I think this is only the tip of the iceberg.

There have been certain drugs that have turned it around for patients. Five or ten years ago, you knew with their diagnosis that their prognosis was not great, and yet now you're seeing patients with exactly the same type of disease out of treatment and going strong.

Do you think that there will ever be a cure for cancer?
I think it's really difficult to say that there is going to be one single cure for cancer. The trouble is cancer is such an umbrella term. You've got so many different sorts of cells in your body, and cancer can affect different types of cells in different ways.

I think that as we've seen such a big change in survival rates in the last ten or 15 years, in the next ten or 15 years you're going to see big breakthroughs that are going to make huge differences. We still don't have a cure for cancer, but more people are surviving cancer and their quality of life is better with their treatment, and I think that will continue.

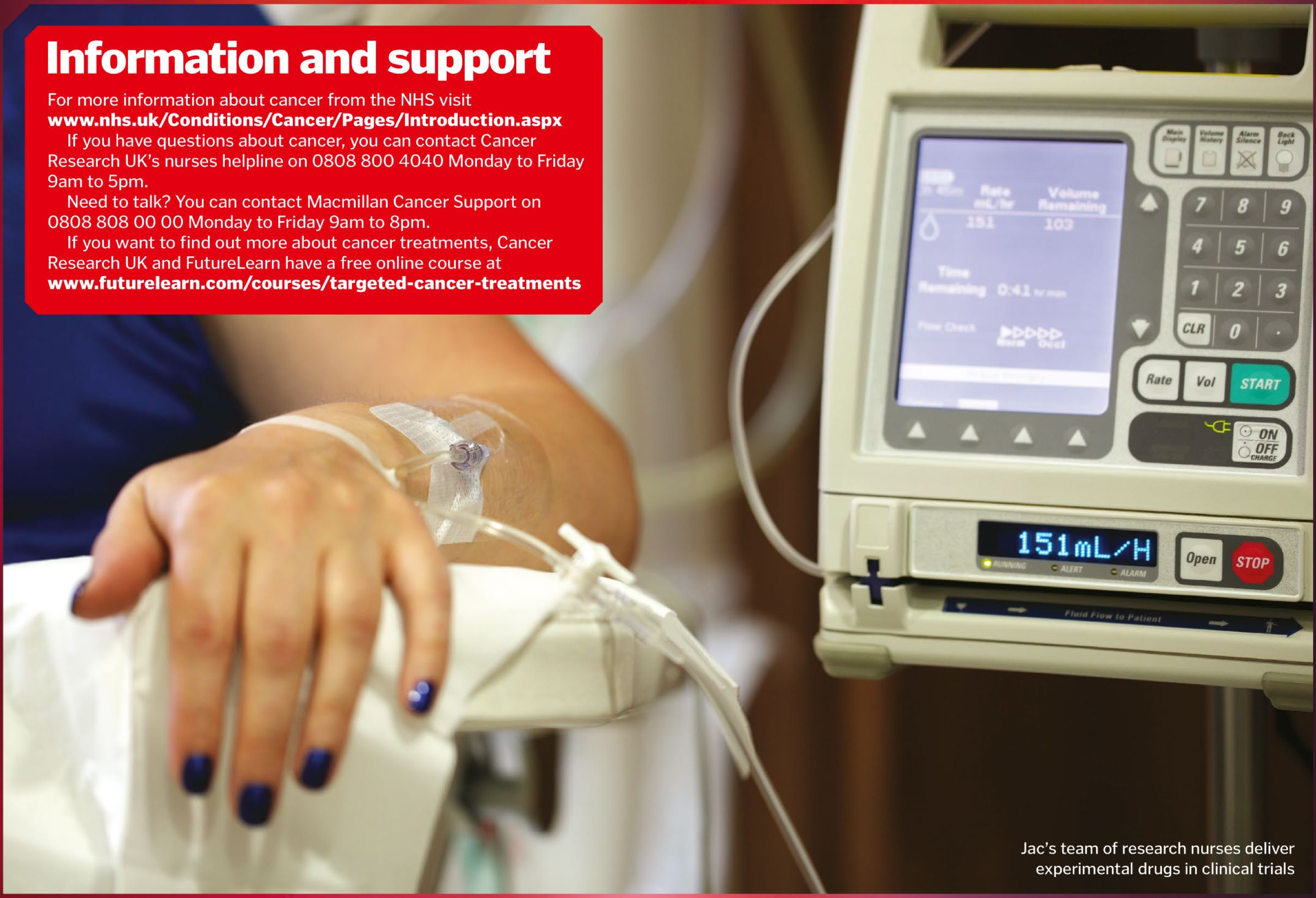
Information and support

For more information about cancer from the NHS visit **www.nhs.uk/Conditions/Cancer/Pages/Introduction.aspx**

If you have questions about cancer, you can contact Cancer Research UK's nurses helpline on 0808 800 4040 Monday to Friday 9am to 5pm.

Need to talk? You can contact Macmillan Cancer Support on 0808 808 00 00 Monday to Friday 9am to 8pm.

If you want to find out more about cancer treatments, Cancer Research UK and FutureLearn have a free online course at **www.futurelearn.com/courses/targeted-cancer-treatments**



Jac's team of research nurses deliver experimental drugs in clinical trials

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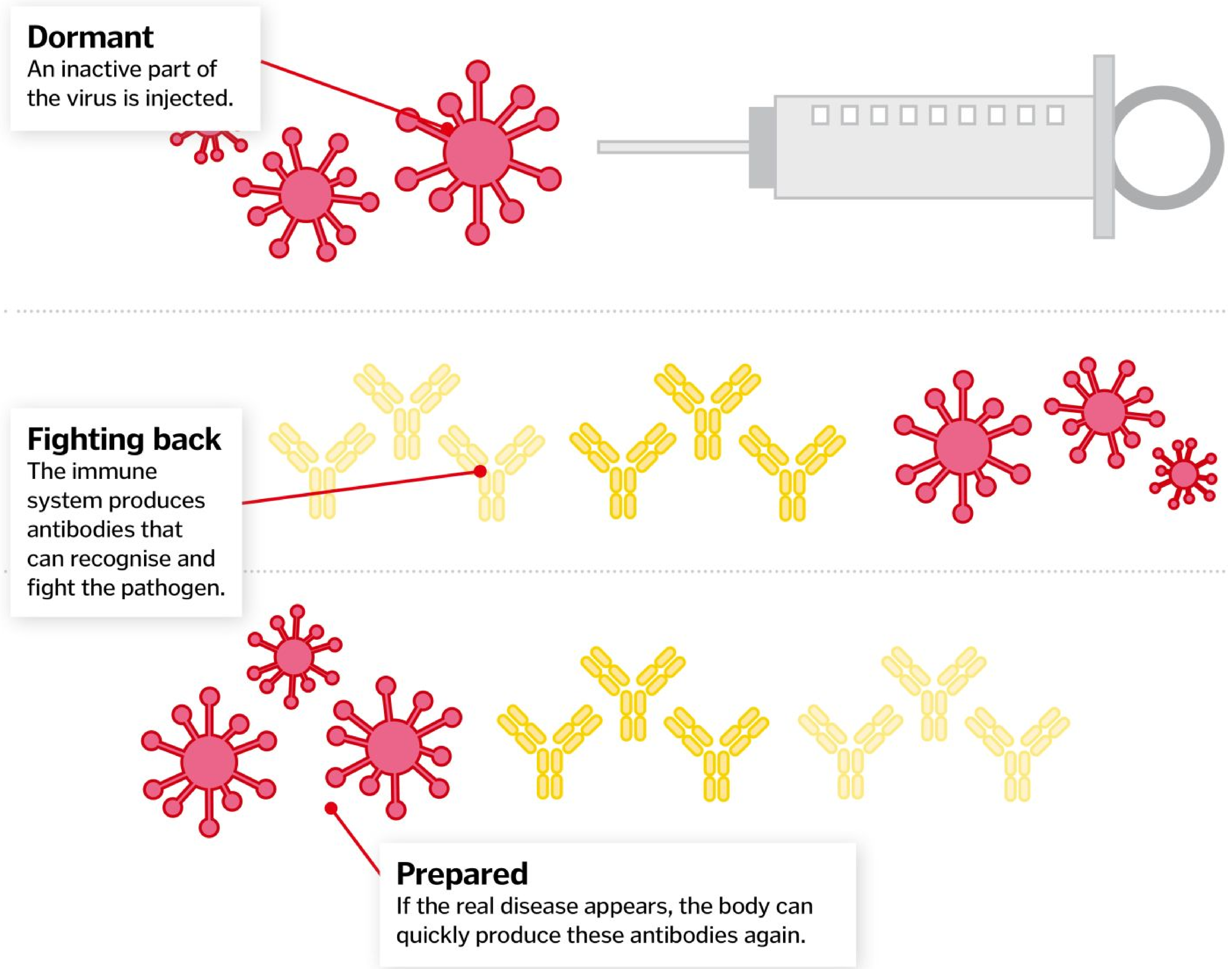
How vaccines work

How we can encourage the body to prepare an army of antibodies to fight disease

When foreign bacteria, viruses or other pathogens enter the body, the immune system responds by producing molecules called antibodies, which recognise and bind to the foreign cells. A vaccine contains a weakened, dead or inactive part of a pathogen, which then triggers the immune system to produce antibodies without causing illness. The harmless invaders are eliminated, but some of the antibodies remain. Should the real disease ever appear, the antibodies will be ready to destroy it.



Dormant
An inactive part of the virus is injected.

Fighting back
The immune system produces antibodies that can recognise and fight the pathogen.

Prepared
If the real disease appears, the body can quickly produce these antibodies again.

What is DNA?

The incredible instruction manual packaged inside our cells

DNA is a complex molecule made up of chains of four different building blocks called nucleotides. The sequence of nucleotides acts like a code, instructing the cell to make certain proteins at certain times, driving biological processes in the body. DNA is found inside most cells and is passed on from parents to their children. Variations in the sequence result in different characteristics, such as eye colour or blood group, and can also lead to genetic disorders such as cystic fibrosis. Advances in our understanding of DNA could mean that in the future, genetic disorders will be treated with 'personalised' medicine that has been tailor-made for your DNA.

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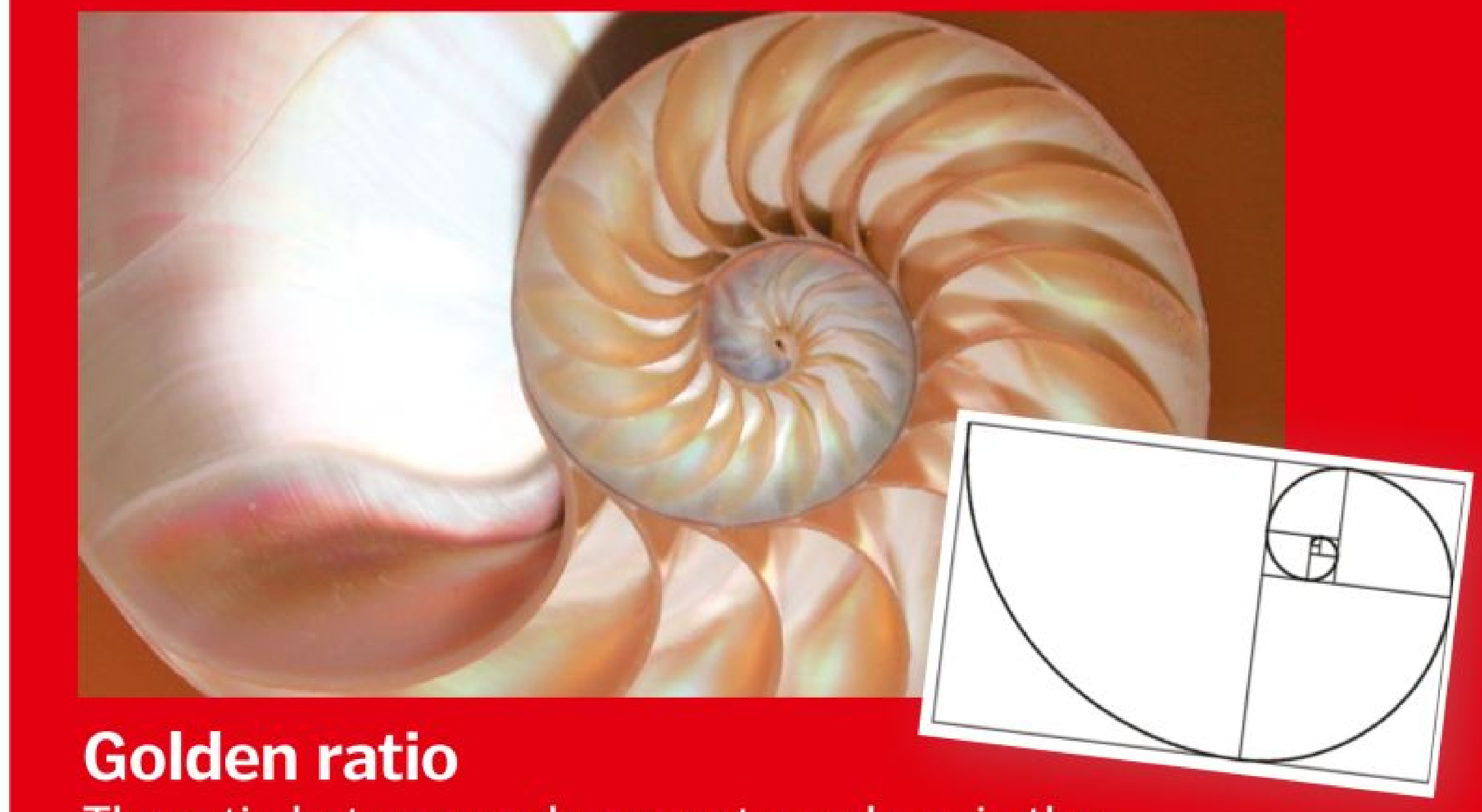
Hidden maths

How numbers, patterns and ratios shape nature

Fibonacci Sequence
In the Fibonacci Sequence, each number is the sum of the previous two: 1, 1, 2, 3, 5, 8, 13, 21 and so on. Many flowers have a Fibonacci number of petals, and seed heads are often arranged in intricate Fibonacci spirals.



Golden ratio
The ratio between subsequent numbers in the Fibonacci Sequence (close to 1.618) is known as the 'golden ratio'. This ratio is frequently found in complex patterns in nature, such as the spiral of a snail's shell.

Fractals
These never-ending patterns are created by repeating the same process. An example is the 'dome' of a Romanesco broccoli, which is divided into smaller, identical domes, themselves divided again, and so on.

Symmetry
Butterfly wings are bilaterally symmetrical, while a starfish is an example of radial symmetry. Nature's examples of symmetry range from the arrangement of a snowflake to the vast structure of the Milky Way.

Inside our stem cells

The cells that are full of potential and replenish the body's specialised tissues

Stem cells are the source of every tissue and organ in the body. Inside an embryo a cluster of stem cells continuously divides. With each division the resulting cells develop different characteristics that mean they can perform specialised functions, a process known as differentiation. Eventually, these cells will go on to form skin, muscle, bone and every other part of the body. Stem cells can also divide to produce identical copies of themselves, so that the body's supply of stem cells never runs out. This property is known as 'self-renewal'.

Even a fully grown organism needs a constant supply of new cells to grow, repair damage or just keep functioning as normal. Many types of cells with specialised functions – such as red blood cells, neurons or skeletal muscle fibres – are unable to divide and replace themselves. Instead, the body has a reservoir of stem cells ready to divide and develop into the cell type that is required. The two key abilities of stem cells – differentiation and self-renewal – mean they could be incredibly useful for studying and treating disease.

In the past, stem cell research has been seen as controversial due to the use of embryonic stem cells, usually taken from embryos left over from fertility treatment. However, more recently, scientists have developed new ways of growing stem cells in the lab, opening up the possibility of exciting new treatments, from building bones to replacing damaged neurons.

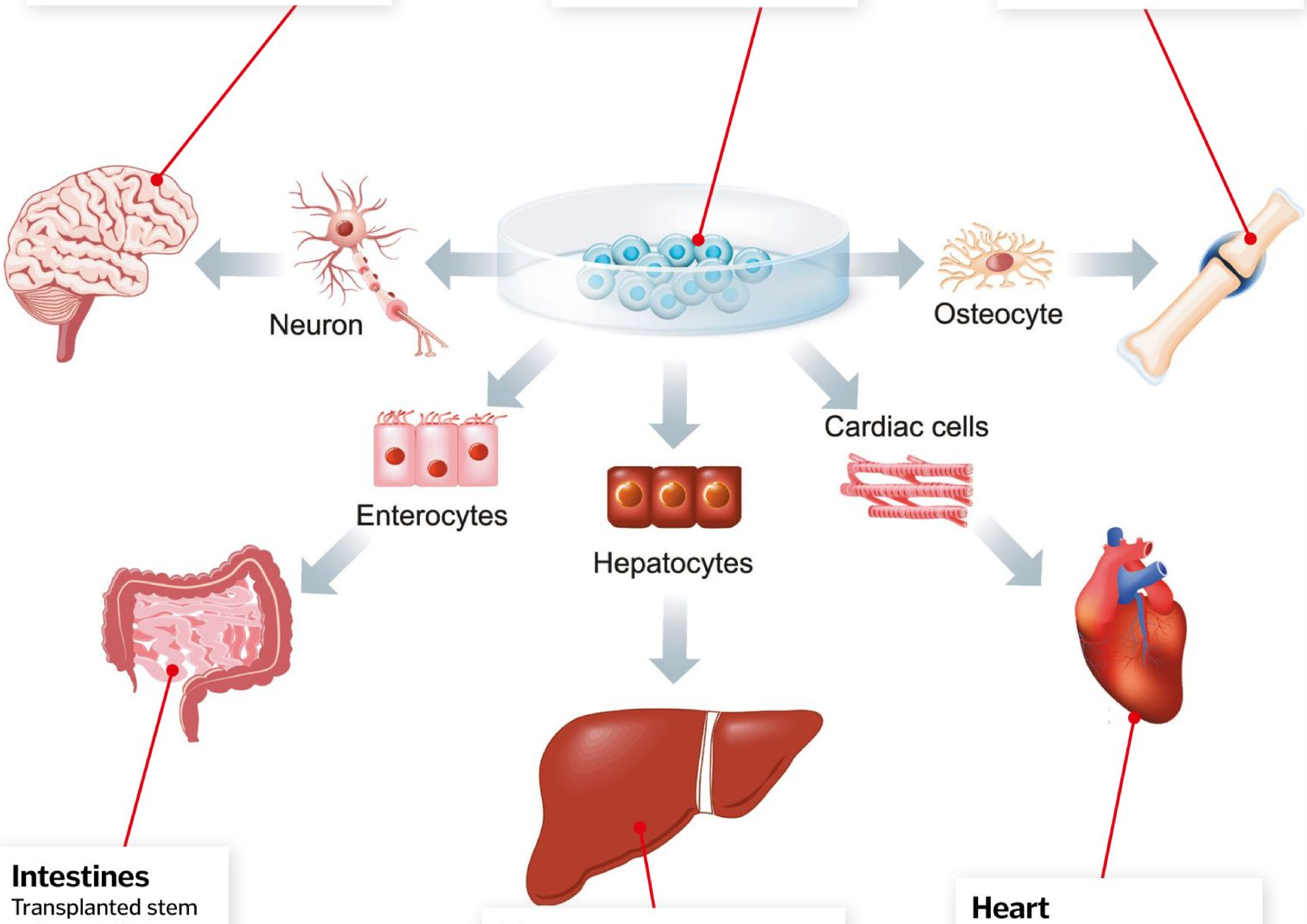
What could stem cells do?

How these remarkable cells could revolutionise medicine

Brain
New, healthy neurons grown from stem cells could be used to replace those lost due to neurodegenerative diseases such as Alzheimer's.

Stem cells
The cells in a patient's skin sample could potentially be reprogrammed into a personalised supply of stem cells.

Bone
Damaged bone or cartilage could be treated with stem cells in order to help the tissue regrow, while avoiding invasive surgery.



Intestines
Transplanted stem cells could help repair damaged intestinal tissue to treat inflammatory bowel disease.

Liver
New liver cells, or hepatocytes, could be made for patients with chronic liver disease, avoiding the need for a transplant.

Heart
Healthy cardiac muscle cells could be grown inside the lab and transplanted into patients with chronic heart disease.

> "A reservoir of stem cells is ready to divide and develop into any cell type"

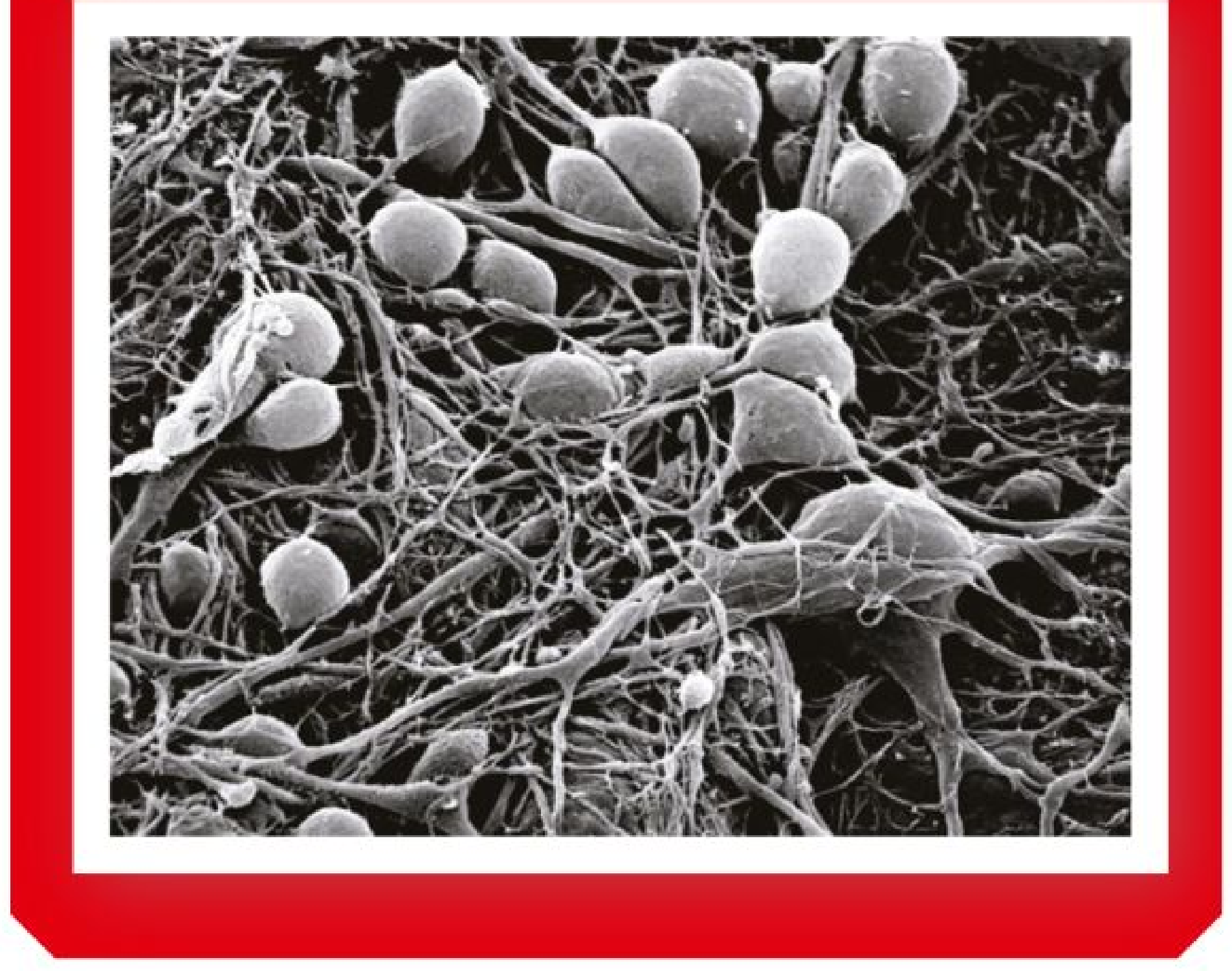
Types of stem cell

Totipotent	Pluripotent	Multipotent
Found in: Zygotes	*Found in: Embryos*	*Found in: Tissues, organs and bone marrow*
Able to develop into an entire organism, plus the embryonic tissues.	Able to develop into any of the cell types inside the adult body.	Produce the cell types found in one kind of organ or tissue.

Making stem cells in the lab

The only natural pluripotent stem cells are those found in embryos. However, in 2006, Japanese scientist Shinya Yamanaka found a way to 'reprogramme' specialised cells found in adults, transforming them into stem cells. Starting with skin cells, Yamanaka was able to reverse the cell differentiation by adding four key genes. The resulting cells were named induced pluripotent stem cells, or iPSCs.

Already, the use of iPSCs in research has enhanced our understanding of genetic conditions including Parkinson's, muscular dystrophy and Down's syndrome. Although there are still technical hurdles to overcome, iPSCs offer the potential to treat many genetic and degenerative diseases by replacing damaged cells with healthy new ones.



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Vitamins and minerals explained

What are micronutrients, and where can you find them?

Vitamins and minerals are essential nutrients. The body needs them to survive, but in much smaller amounts than nutrients like protein, carbohydrates and fats.

The body is made of cells, which are essentially tiny molecular factories. They are surrounded by a fatty membrane, they use carbohydrates for fuel, and most of the molecules they produce come in the form of proteins. So, the body needs large amounts of fats, carbs and proteins to survive, but it also requires small quantities of micronutrients. Vitamins and minerals are used to produce crucial molecules like enzymes and hormones, which help the body to maintain its balance of fluids, to send short- and long-distance signals, and to strengthen and repair tissues.

Vitamins are organic and made by other living organisms, while minerals are inorganic – most often metals – and are found in the soil. The human body cannot produce them by itself, so we need to take them in through our diets.

There are two main types of vitamin, categorised according to how they dissolve. Fat soluble vitamins can be found in foods like oils, dairy products, eggs, liver and fish, and they are also stored in the fats inside the body. This helps to prevent deficiency, but it means that it is possible to overdose if you eat too much. In contrast, water soluble vitamins cannot be stored by the body. They are found in fruits, vegetables, grains and dairy products, and any excess is rapidly excreted in the urine. This makes it harder to overdose, but easier to become deficient.

Luckily, a healthy, balanced diet is usually enough to ensure that you have the right mixture of vitamins and minerals to keep your body functioning normally.

V Vitamin B2 aka riboflavin
Milk, eggs, fortified cereals
B2 is involved in releasing energy, and it's also an antioxidant that helps to scavenge free radicals.

V Vitamin D
Oily fish, red meat, made from sunshine
This vitamin is important in maintaining the right amount of calcium and phosphate, critical for strong bones.

V Vitamin B12
Meat, fish, milk
B12 is involved in healthy nerves and red blood cells, and helps the body process folic acid.

V Vitamin B5 aka pantothenic acid
Chicken, beef, potatoes
B5 is used to make Coenzyme A, which breaks down fats and carbs.

M Phosphorous
Red meat, poultry, oats
This mineral is found in every cell in the body, and it helps strengthen bones.

M Zinc
Meat, shellfish, wheat germ
Zinc is important for making new cells and enzymes.

V Vitamin B6 aka pyridoxine
Pork, chicken, fish
B6 is involved in the storage of energy, and in making red blood cells.

V Vitamin A
Eggs, cheese, oily fish
Vitamin A is needed for the production of light-sensitive pigments in the eye. It's also involved in immune function and skin health.

V Vitamin C aka ascorbic acid
Citrus fruits, strawberries, blackcurrants
This vitamin is involved in the production of collagen, which supports the skin and other tissues.

V Vitamin B3 aka niacin
Liver, fish, wheat, sunflower seeds
B3 is involved in breaking carbohydrates down into the simple sugar glucose.

V Vitamin E
Plant oils, nuts, seeds
Vitamin E is an antioxidant that helps to neutralise free radicals. It's important for skin, eyes and the immune system.

V Folic acid aka folate
Broccoli, sprouts, liver
Folic acid is involved in the development of the nervous system – crucial during pregnancy.

M Potassium
Bananas, broccoli, pulses
Potassium works with sodium to pass signals along the nerve cells, helping the heart to function.

M Molybdenum
Nuts, cereals, peas, beans
Molybdenum helps enzymes involved with making and repairing genetic materials.

V Vitamin B1 aka thiamin
Fortified cereals, nuts and meats
The first of eight B vitamins involved in breaking down fats and carbs to release energy.

M Chromium
Meat, whole grains, broccoli
Chromium is involved in insulin signalling and maintaining blood sugar levels.

M Copper
Nuts, shellfish, offal
This metal is involved in making blood cells.

V Vitamin B7 aka biotin
Eggs, nuts, whole grains
This vitamin is essential for the metabolism of fat.

M Selenium
Brazil nuts, fish, meat
Selenium is an ingredient in enzymes that help prevent cell damage.

V Vitamin K
Green leafy vegetables, cereals
Vitamin K is crucial for blood clotting. It is a component of many of the clotting factors that help to stop bleeding after injury. It also plays a role in bone health.

M Manganese
Tea, cereals, peas
Manganese helps with clotting and is important in connective tissue and bone.

M Calcium
Dairy products, green leafy vegetables, soya beans
This is the most abundant mineral in the body. It is used to build strong bones, and is involved in the signals that contract and relax muscles.

M Iodine
Seafood, iodised table salt
Iodine is vital for making thyroid hormones, which are responsible for regulating metabolism.

M Magnesium
Green leafy vegetables, brown rice, whole grains
This mineral helps the parathyroid glands produce hormones important for bone health.

M Iron
Meat, beans, dark green leafy vegetables
Iron is a key component of haemoglobin – the red pigment that carries oxygen around the blood.

M Sodium
Table salt
Salt contains sodium and chloride, both crucial for fluid balance, and sodium is vital for nerve signalling.

KEY:
V Vitamin
M Mineral

MIND TRICKS

Discover the mind-bending illusions that prove you shouldn't always believe what you see or feel

As you go about your daily life, your brain continuously perceives the world around you with the help of your senses. The constant stream of information it receives is overwhelming, so it regularly takes shortcuts to simplify what you see or feel and chooses the most likely interpretations. This helps it to concentrate on what's important, rather than focusing on everything at once. The brain is also very good at predicting the future, helping it to compensate for the slight delay between you physically seeing or touching something and receiving and processing those signals from your eyes or limbs. However, these shortcuts and predictions also make it possible for your brain to be fooled.

Humans have been discovering ways to trick the mind for millennia, with examples of optical illusions found in Stone Age cave paintings. Ancient Greek philosopher Aristotle noted that "our senses can be trusted but they can be easily fooled" with an illusion now referred to as the waterfall effect. While watching a waterfall he noticed that shifting his gaze from the moving water to the static rocks made the rocks appear to move in the opposite direction to the flow of water. Now known as 'motion aftereffect', it's caused by the wearing out of certain neurons in the brain as they perceive motion. When you move to look at the rocks, competing neurons overcompensate for those that are worn out, creating the illusion of movement.

Studying how the brain reacts to illusions has become much easier since Aristotle's day. Functional magnetic resonance imaging (fMRI) allows scientists to analyse the processes going on inside our heads as we experience certain images or situations, examining how the brain responds in real time. However, there is still a great deal more to be explored, as our responses to some illusions remain a mystery.

How we see

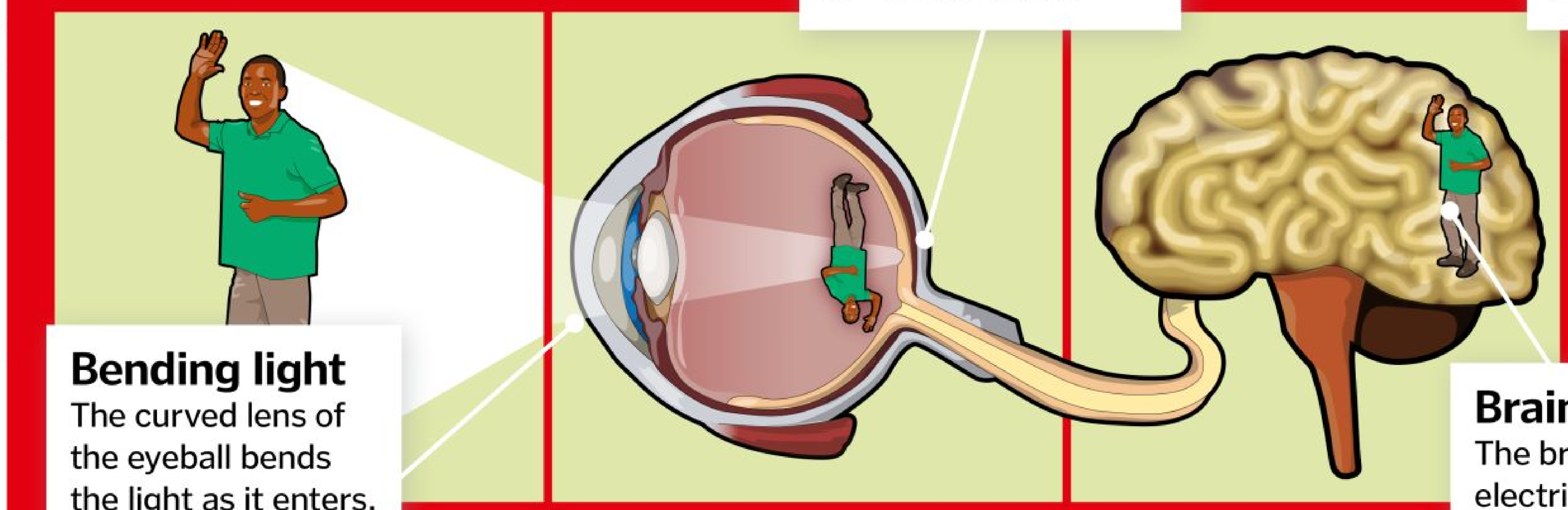
Your eyeballs are your window to the world, enabling your brain to create colourful three-dimensional moving images of your surroundings in amazing detail. They work a bit like a camera, allowing light to enter through a lens, which then focuses it onto a kind of sensor called the retina. Your eyes can even zoom like a camera, as muscles help to flatten the lens to see distant objects, or thicken it to see things close-up.

Once the light hits the retina, it is detected by light-sensitive cells called rods and cones. Rods are responsible for our sight in dark conditions, allowing us to see in monochrome, while cones allow us to see colour and detail in brighter conditions. When the light hits them, chemicals in the rods and cones change, creating an electrical signal that is sent to the brain.

Here the information from each eye is combined and compared so that an image of your surroundings can be accurately reconstructed with plenty of depth and contrast. This whole process takes about a hundredth of a second, enabling you to see the world almost in real time.

The human eye

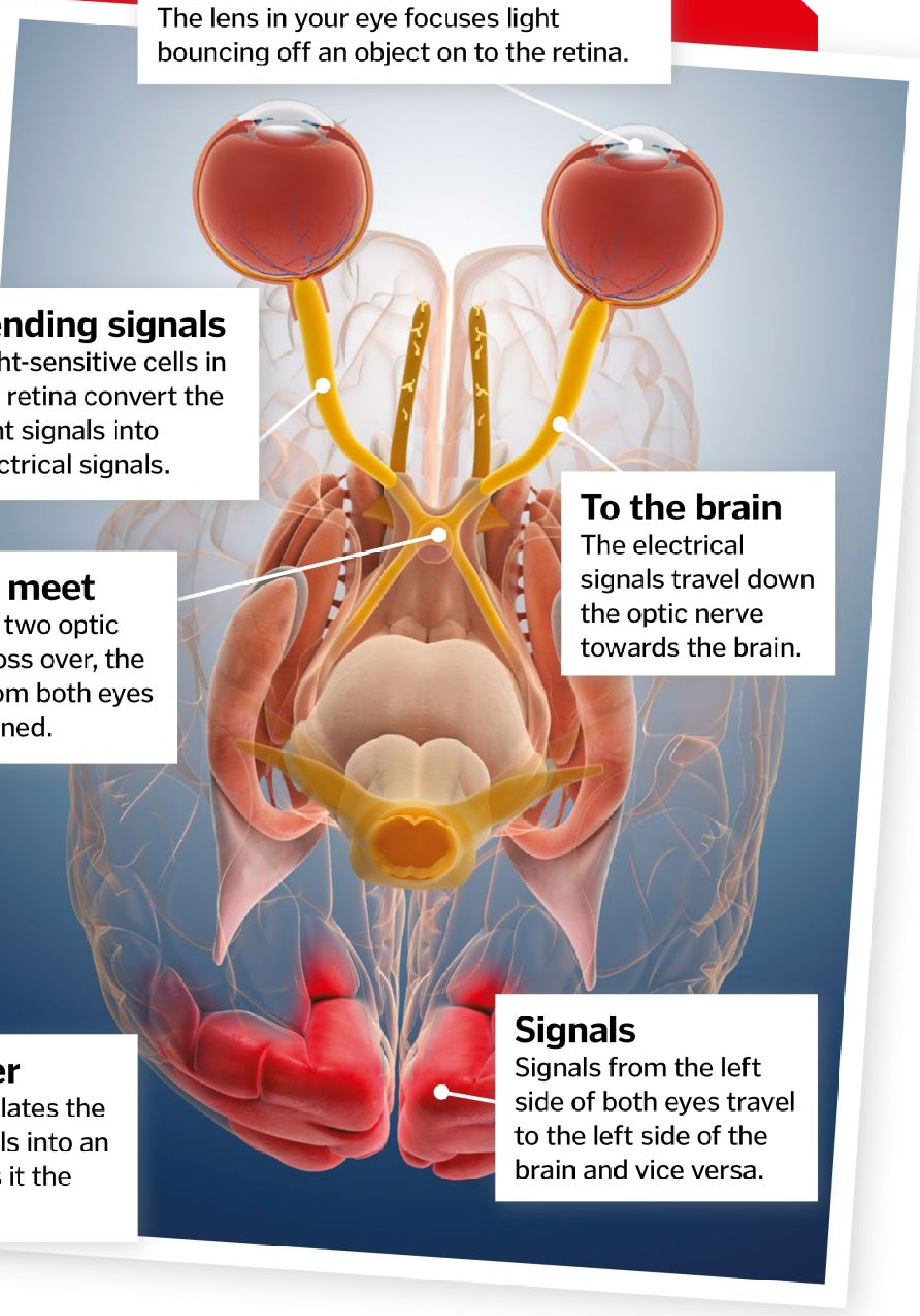
How do we turn waves of light into images of our surroundings?



Wrong way up
The light signals received by the retina are upside down.

Bending light
The curved lens of the eyeball bends the light as it enters.

Brain power
The brain translates the electrical signals into an image and flips it the right way up.



Light enters
The lens in your eye focuses light bouncing off an object on to the retina.

Sending signals
Light-sensitive cells in the retina convert the light signals into electrical signals.

To the brain
The electrical signals travel down the optic nerve towards the brain.

Nerves meet
When the two optic nerves cross over, the signals from both eyes are combined.

Signals
Signals from the left side of both eyes travel to the left side of the brain and vice versa.

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“Humans have been discovering ways of tricking the mind for millennia”

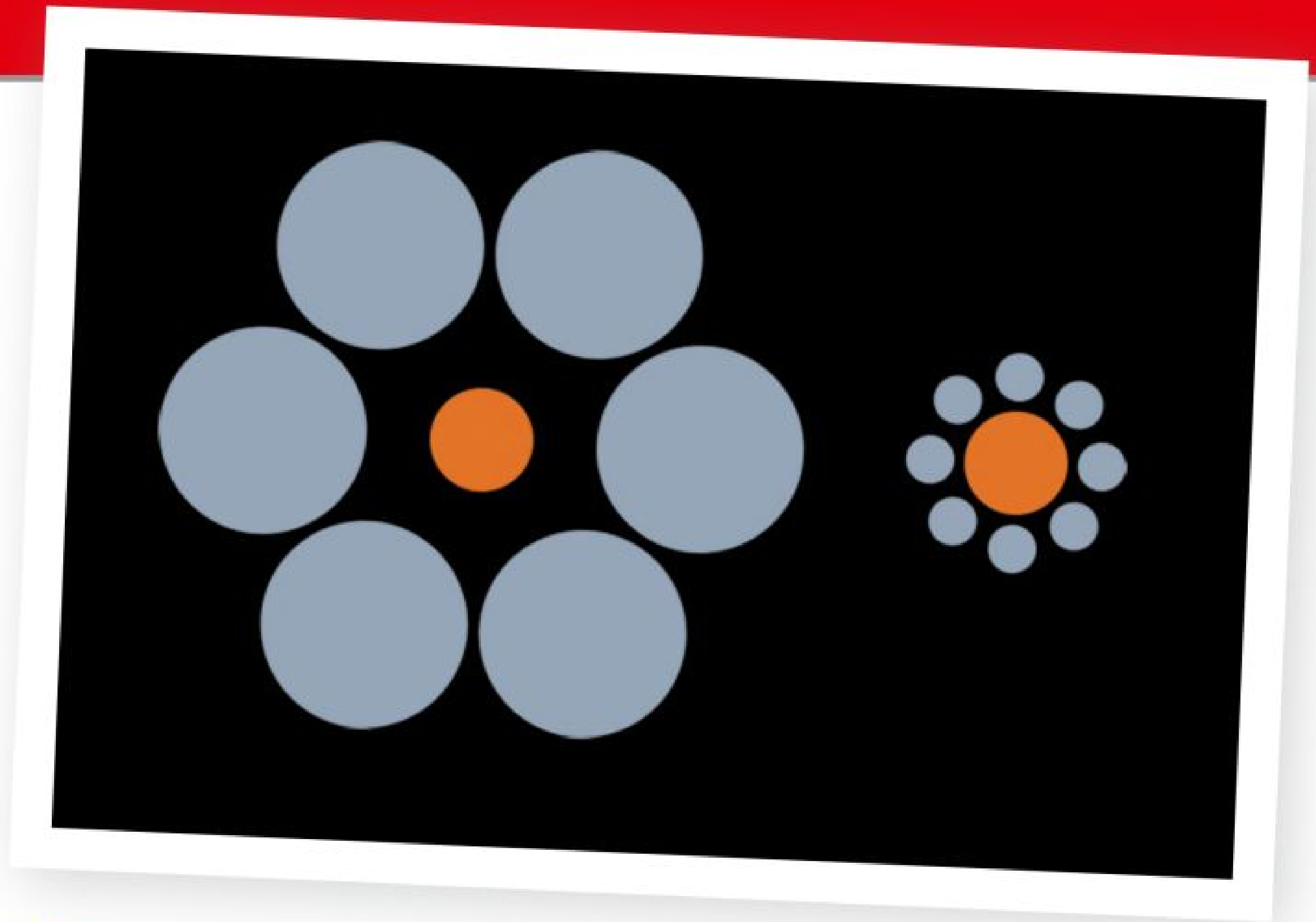
Size illusions

Discover how context can mask an object's true size

When you look at two objects next to each other, you are probably pretty confident in identifying whether they are the same size or if one is bigger than the other. However, there are certain optical illusions that prove you might not always get it right. That is because our brains often make judgements about the size of an object based on other objects that are nearby, and so can easily be fooled by context.

Take, for example, the Ebbinghaus illusion on the top right of this page. Many would consider the orange circle on the right to be larger than the one on the left, but they are in fact both exactly the same size. The brain uses the blue circles to judge the orange circles' size, and so because the blue circles on the left are larger, the left orange circle seems smaller in comparison.

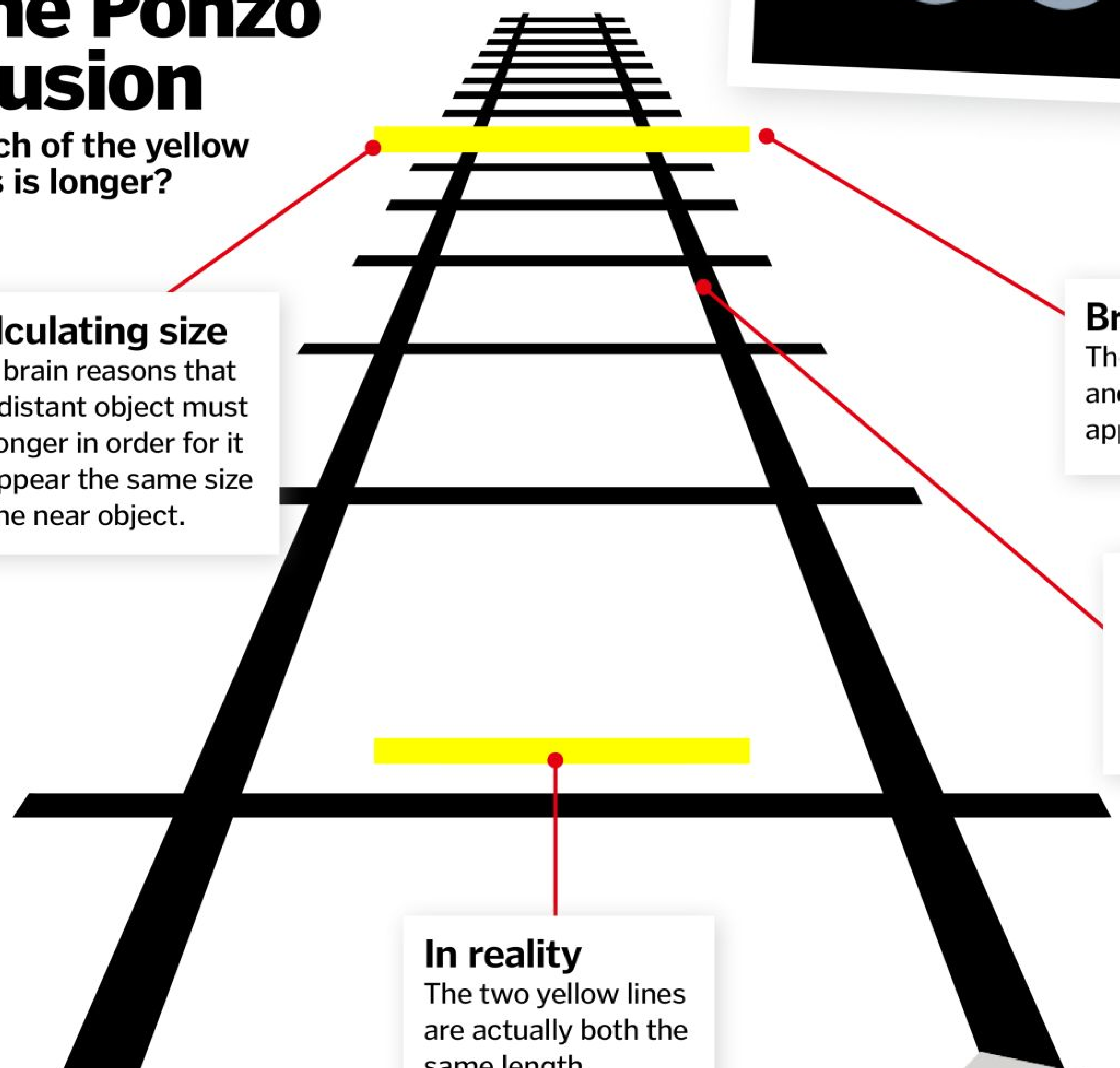
Context can also affect our brain's depth perception, making objects seem nearer or further away than they really are. This in turn can influence how we perceive their size, as illustrated by the Ponzo illusion shown here. It's this particular mind trick that makes the Moon appear bigger when it's near the horizon.



The Ebbinghaus illusion illustrates how context affects size perception

The Ponzo illusion

Which of the yellow lines is longer?



Calculating size
The brain reasons that the distant object must be longer in order for it to appear the same size as the near object.

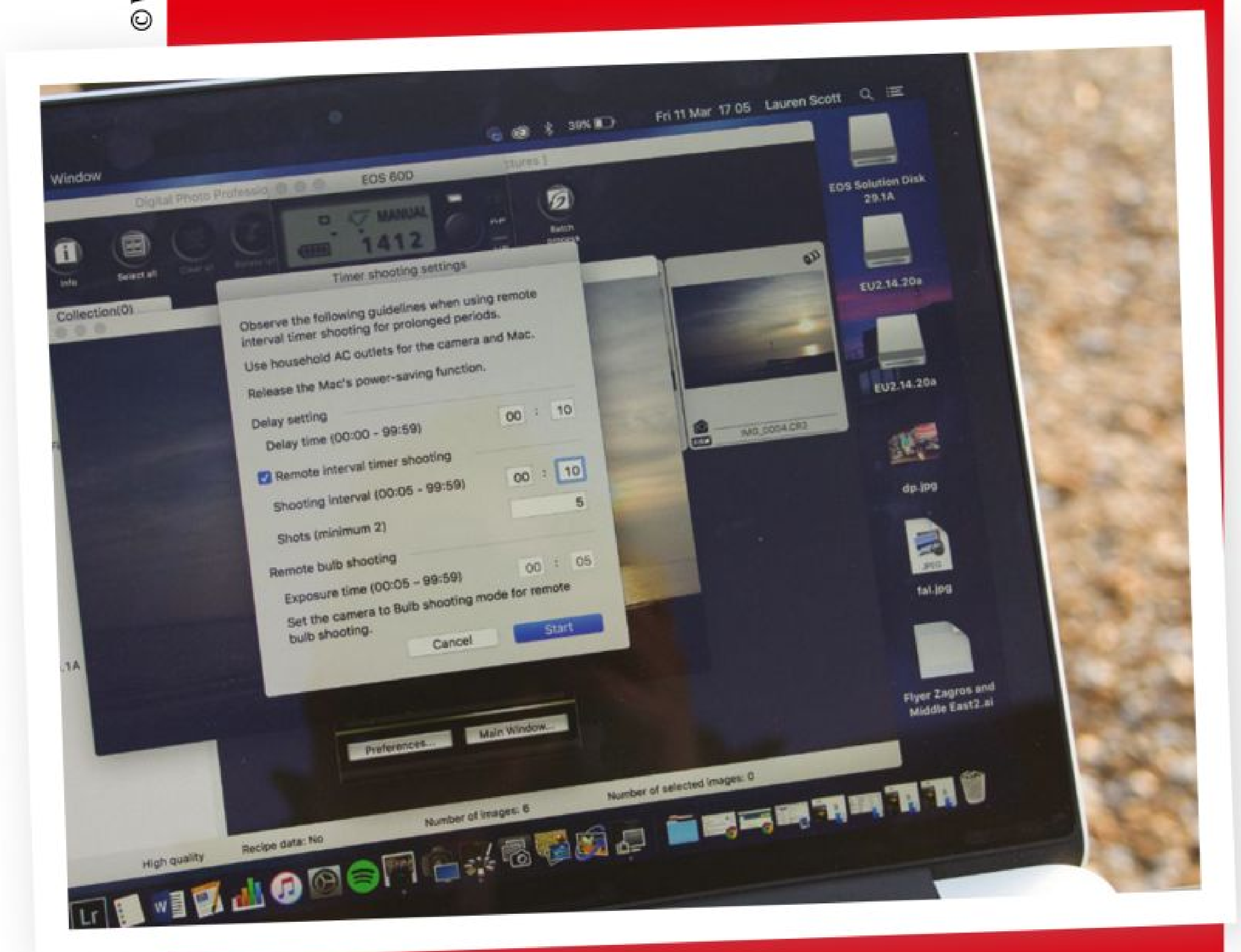
Brain fooled
The brain overcompensates and makes the top line appear longer.

In the distance
The converging parallel lines trick the brain into believing that the top line is further away.

In reality
The two yellow lines are actually both the same length.

Screen flicker

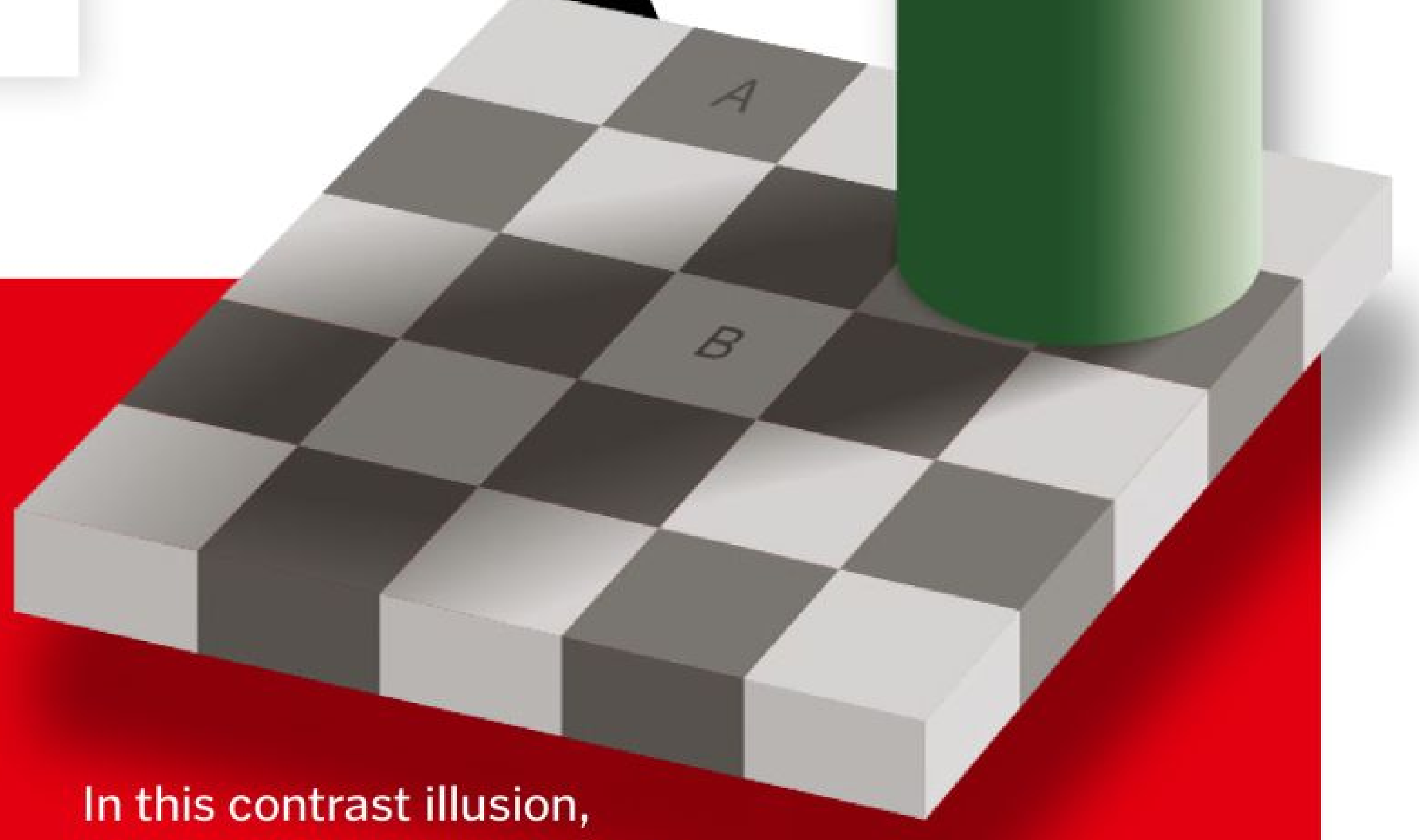
If an LCD screen is filmed with a video camera, the screen often appears to flicker. This is because the screen is actually flickering in real life, and it's our eyes that are being fooled into seeing a continuous image. When a camera captures a scene, it takes a series of rapid shots and stitches them together to create a moving image. Therefore, if its frame rate does not match that of the screen it is filming, it picks up the flickering. Our eyes, on the other hand, are constantly sending information to our brains, and so hang onto an afterimage of the light from the screen in order to fill in the gaps caused by the flickering.



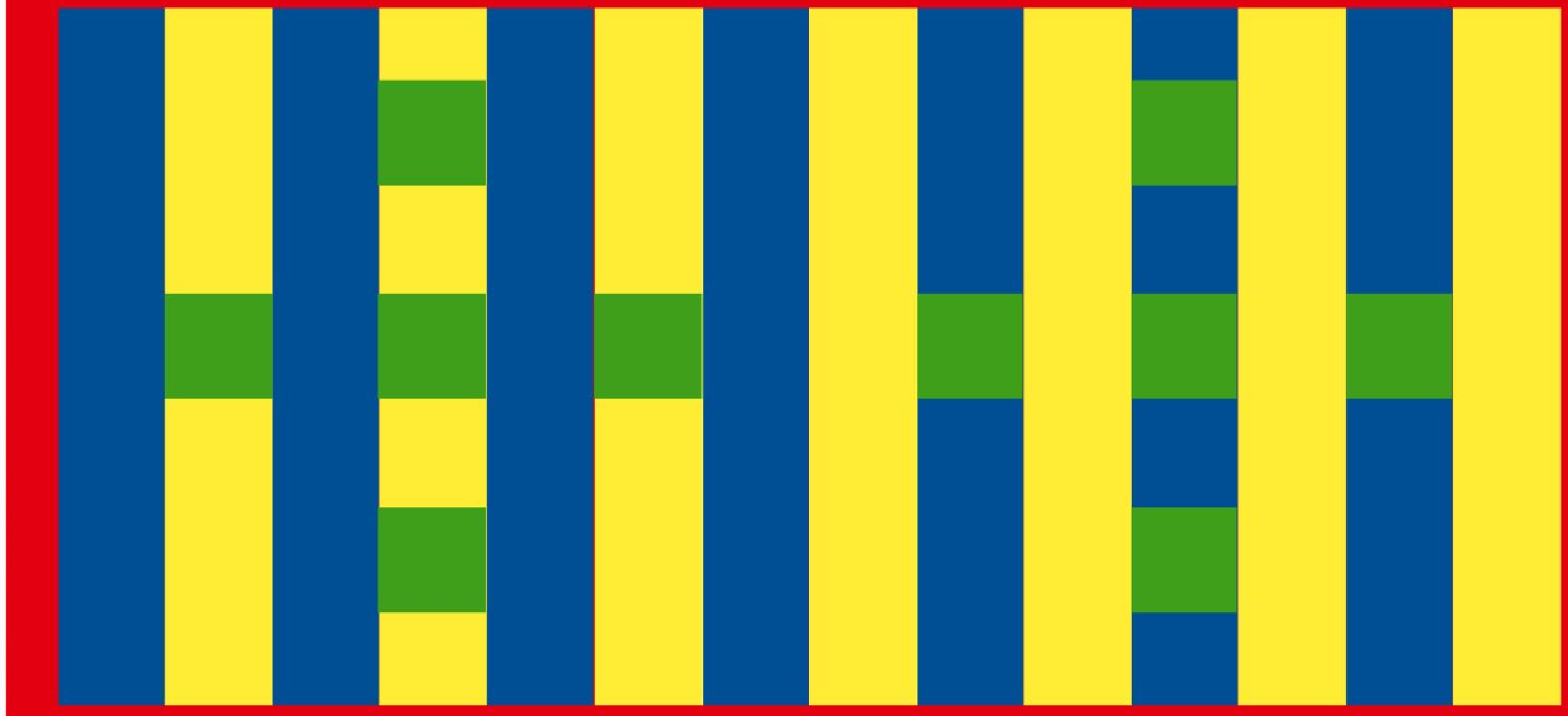
LCD screens rapidly switch their power on and off in order to regulate their brightness

Contrast illusions

As well as altering how we perceive an object's size, context can also affect how we perceive its colour. In this image, all of the green squares are exactly the same shade, but the ones on the left appear darker than those on the right. This is because the green squares on the left are on a lighter background, creating more contrast and so making them appear darker in comparison to their surroundings. This simultaneous contrast illusion is believed to be caused by the way the retina's light-sensitive cells process two different colours next to each other. When the light reflected from a brighter background hits one of these cells, any adjacent cells are inhibited from firing off signals. This causes the light reflected from the green squares on the left to activate a stronger signal, making them appear darker.

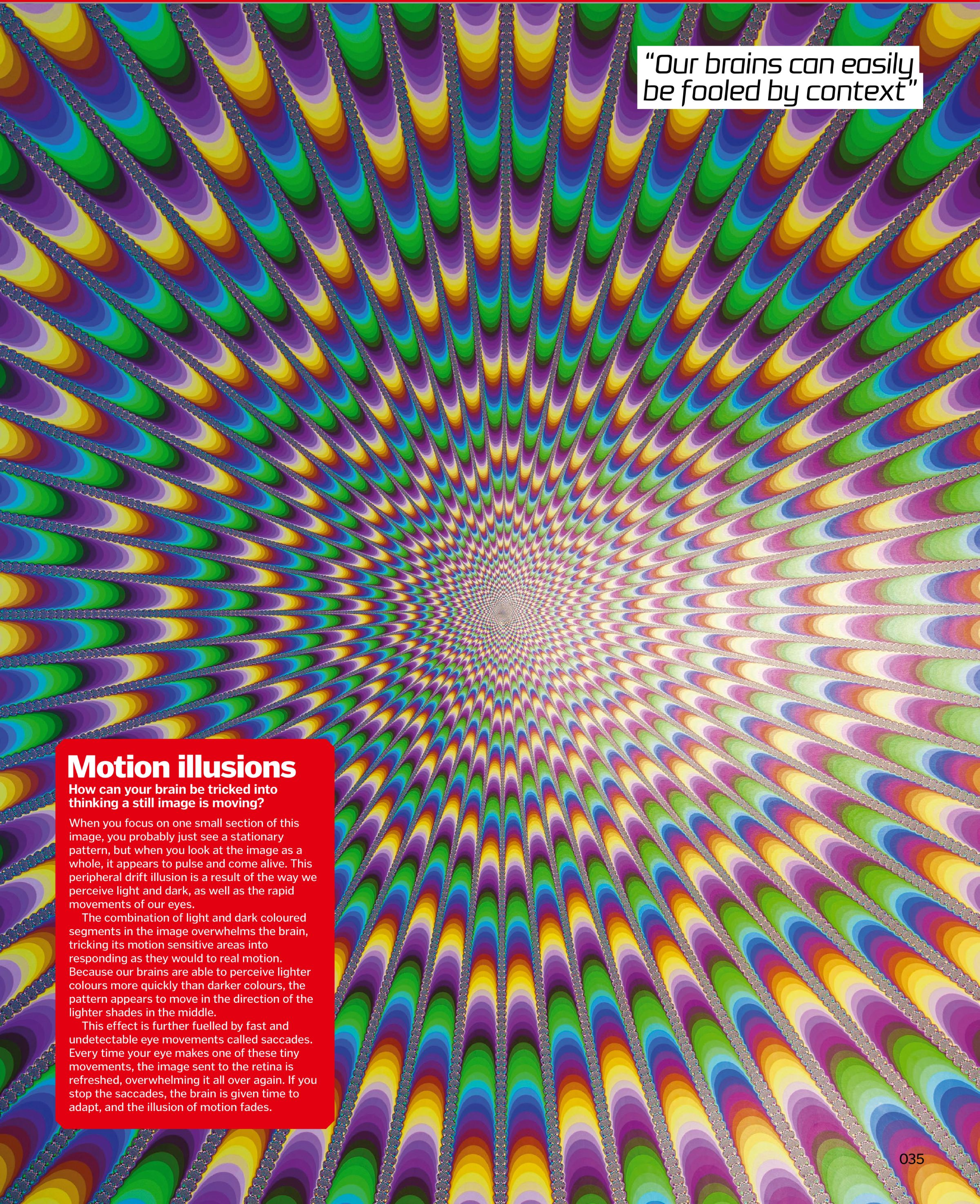


In this contrast illusion, squares A and B are actually the same shade of grey



The green squares on the yellow background appear darker than those on the blue background

© WIKI; Thinkstock



“Our brains can easily be fooled by context”

Motion illusions

How can your brain be tricked into thinking a still image is moving?

When you focus on one small section of this image, you probably just see a stationary pattern, but when you look at the image as a whole, it appears to pulse and come alive. This peripheral drift illusion is a result of the way we perceive light and dark, as well as the rapid movements of our eyes.

The combination of light and dark coloured segments in the image overwhelms the brain, tricking its motion sensitive areas into responding as they would to real motion. Because our brains are able to perceive lighter colours more quickly than darker colours, the pattern appears to move in the direction of the lighter shades in the middle.

This effect is further fuelled by fast and undetectable eye movements called saccades. Every time your eye makes one of these tiny movements, the image sent to the retina is refreshed, overwhelming it all over again. If you stop the saccades, the brain is given time to adapt, and the illusion of motion fades.

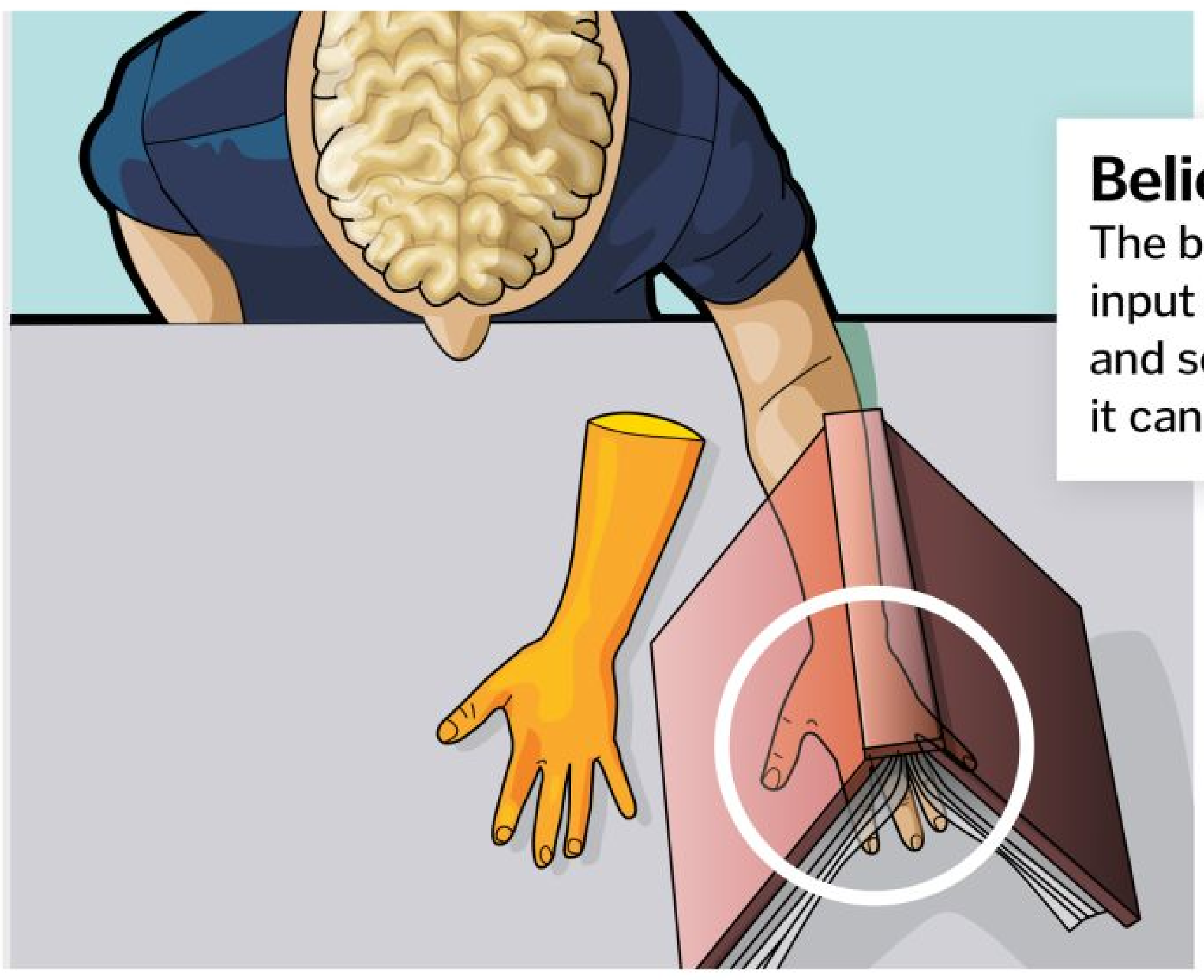
Tricking your body

Fooling your brain can help reduce physical pain and even create pain when there is none

Horizontal lines on clothing affect how our eyes view people's body shape

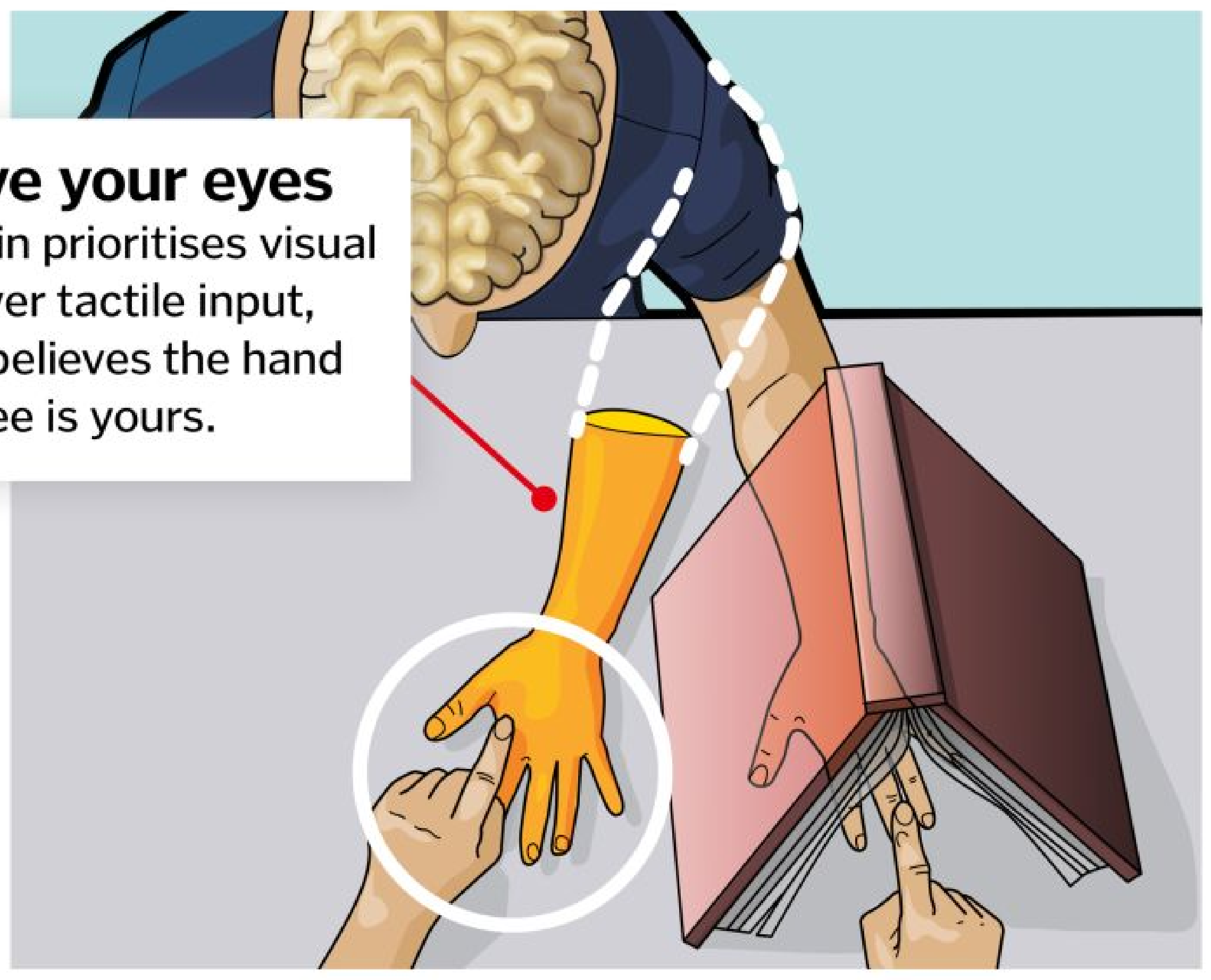
Rubber hand illusion

Trick your mind into believing that a fake hand is your own



1 Hide your hand

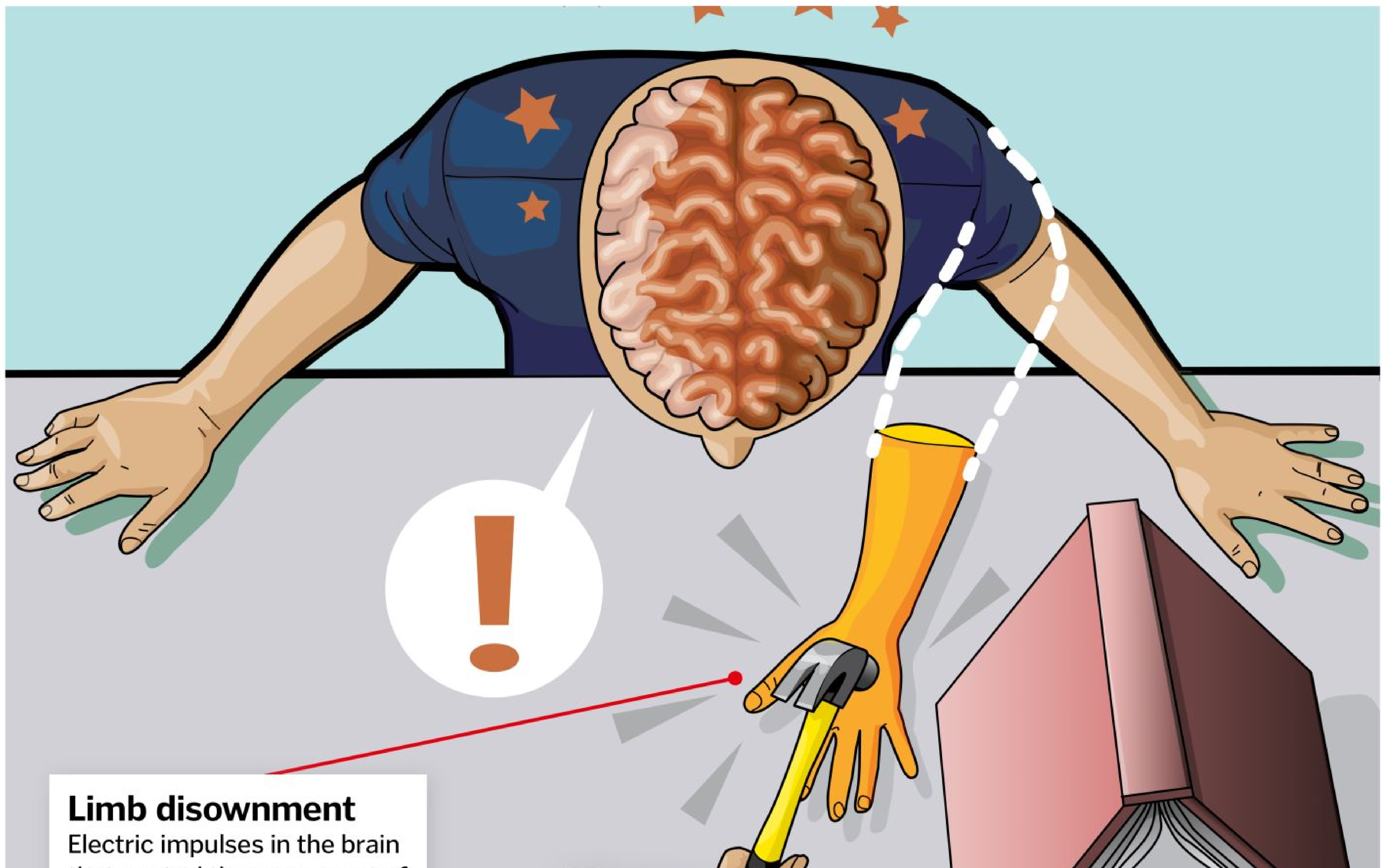
Place an open book on the table in front of you, then sit with one hand underneath the book so that you cannot see it. Put the rubber hand in front of you so that it is lined up with your shoulder. Covering your arm and the 'arm' of the fake hand with a cloth will help the illusion.



Believe your eyes
The brain prioritises visual input over tactile input, and so believes the hand it can see is yours.

2 Start stroking

Get a friend to stroke the middle finger of your real hand and the middle finger of the fake hand at the same time. After one or two minutes you will start to feel like the fake hand is your own and that your real hand no longer exists.



Limb disownment
Electric impulses in the brain that control the movement of your hand weaken, making it feel like it is no longer there.

3 Inflict some pain

Get your friend to then hit the rubber hand with a hammer. You should feel a brief jolt of pain as your brain combines visual and physical information to create a feeling of ownership over the fake hand.

Body illusions can be used to help amputees alleviate phantom limb pain

Mirror therapy

The ability to fool the brain into experiencing ownership of a fake body part is proving useful for helping patients with phantom limb pain – the feeling of pain in an amputated or paralysed limb. By placing the affected limb behind a mirror and then moving the opposite, unaffected limb in front of the mirror, the brain can be tricked into thinking the reflection is a real moving body part. This enables the patient to mentally move their phantom limb, perhaps unclenching it from a painful position to provide relief. The illusion works because the brain prioritises visual feedback over tactile feedback and so the observation of movement still manages to stimulate the processes in the brain involved in real movement.

Mirror therapy tricks the brain into thinking a reflected limb is real

Shrinking pain

The brain's tendency to prioritise visual input over tactile input makes it possible to manipulate the experience of pain. In a study conducted by researchers at Oxford University, participants suffering from chronic pain in their right arm were asked to move the limb while looking at it through a pair of binoculars. They were then asked to do the same again, but while looking through the other end of the binoculars. When presented with a magnified view of their arm, every participant reported experiencing an increase in pain, but when their arm looked smaller or further away, the pain, and even the swelling, increased significantly less. Exactly how this illusion works remains unclear. One theory is that magnifying the arm enhances the sense of touch, while another suggests that by 'minifying' the limb, the brain's sense of ownership of it is reduced, thus desensitising it to the pain.

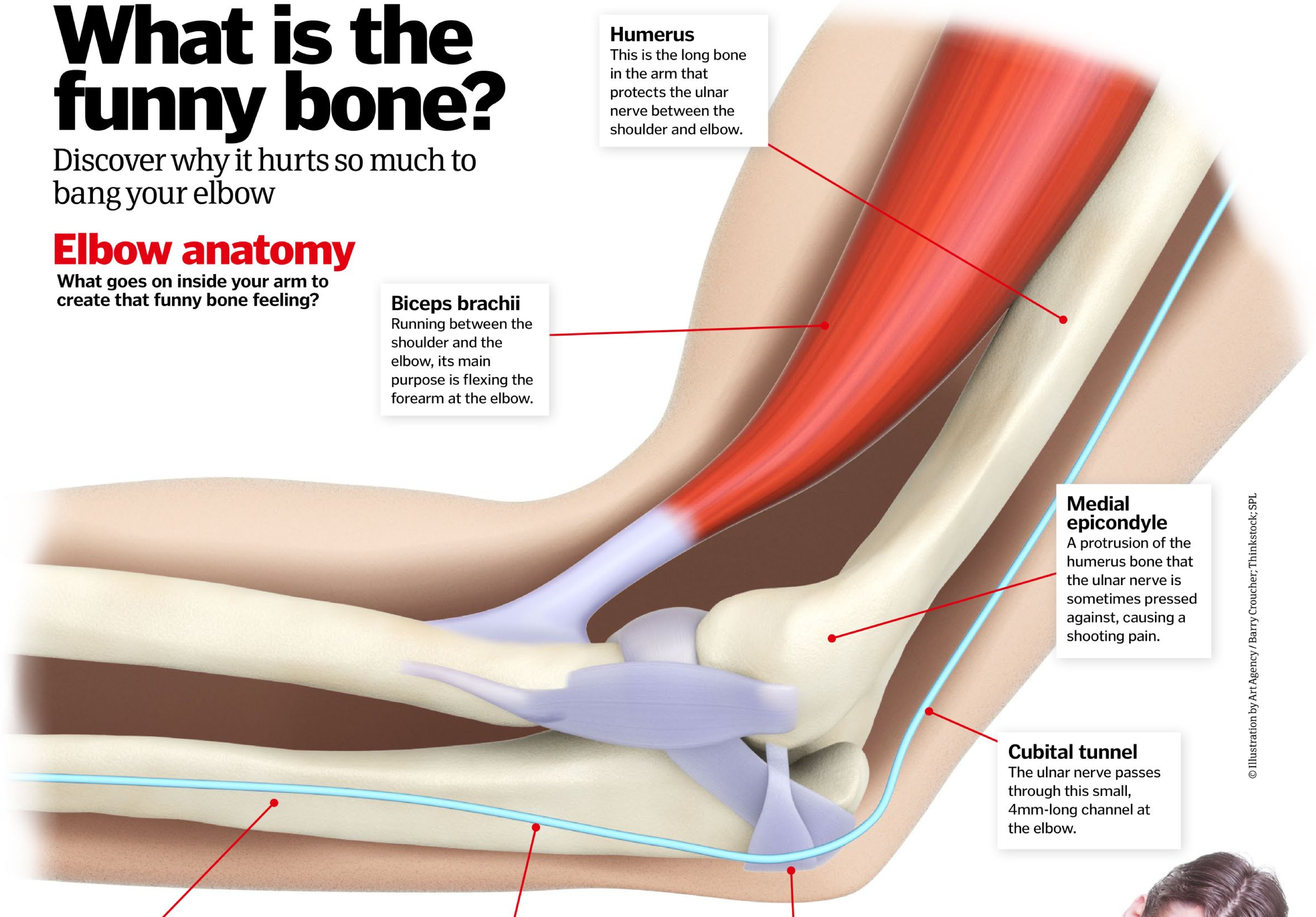
Binoculars have been proven to help reduce physical pain

What is the funny bone?

Discover why it hurts so much to bang your elbow

Elbow anatomy

What goes on inside your arm to create that funny bone feeling?



Humerus
This is the long bone in the arm that protects the ulnar nerve between the shoulder and elbow.

Biceps brachii
Running between the shoulder and the elbow, its main purpose is flexing the forearm at the elbow.

Medial epicondyle
A protrusion of the humerus bone that the ulnar nerve is sometimes pressed against, causing a shooting pain.

Cubital tunnel
The ulnar nerve passes through this small, 4mm-long channel at the elbow.

Ulna
This is the bone in your forearm that runs parallel to the radius and protects the ulnar nerve.

Ulnar nerve
This string of sensitive fibres sends signals to and from the muscles in your arms and hands.

Olecranon
A bony protrusion where the radius and ulna bones meet the humerus bone.

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That unpleasant tingling feeling you get when you knock your 'funny bone' doesn't actually come from a bone at all. Instead it stems from the ulnar nerve, which runs from your neck down to your hands. This nerve is mostly protected by layers of bone and muscle, but at the elbow it passes through the cubital tunnel, where there is only skin for it to hide behind. Therefore, when you hit your arm at just the wrong angle, the nerve is compressed between the skin and a knob of bone called the medial epicondyle, causing it to send a shooting pain down your arm and into your fingers.

The term 'funny bone' is thought to derive from the name of the humerus bone in the upper arm

Hitting your ulnar nerve sends a weird tingling feeling down your arm

What makes us sick?

Nobody likes to throw up, but it's an ancient reflex that protects us against poisoning

The vomit reflex is hard-wired. It's controlled by the brainstem, one of the most primitive parts of the brain, from a spot known as the area postrema, or vomiting centre. The centre receives information from across the digestive system, from parts of the brain involved in processing sight, smell, balance and emotion, and from the chemoreceptor trigger zone, which detects toxins in the blood.

If something isn't right, the area postrema sets off a tightly coordinated reflex. The mouth fills with saliva, shielding the teeth from the effects of stomach acid. The body takes a deep breath before access to the lungs is blocked off. The soft palate in the mouth is raised to cover the nostrils.

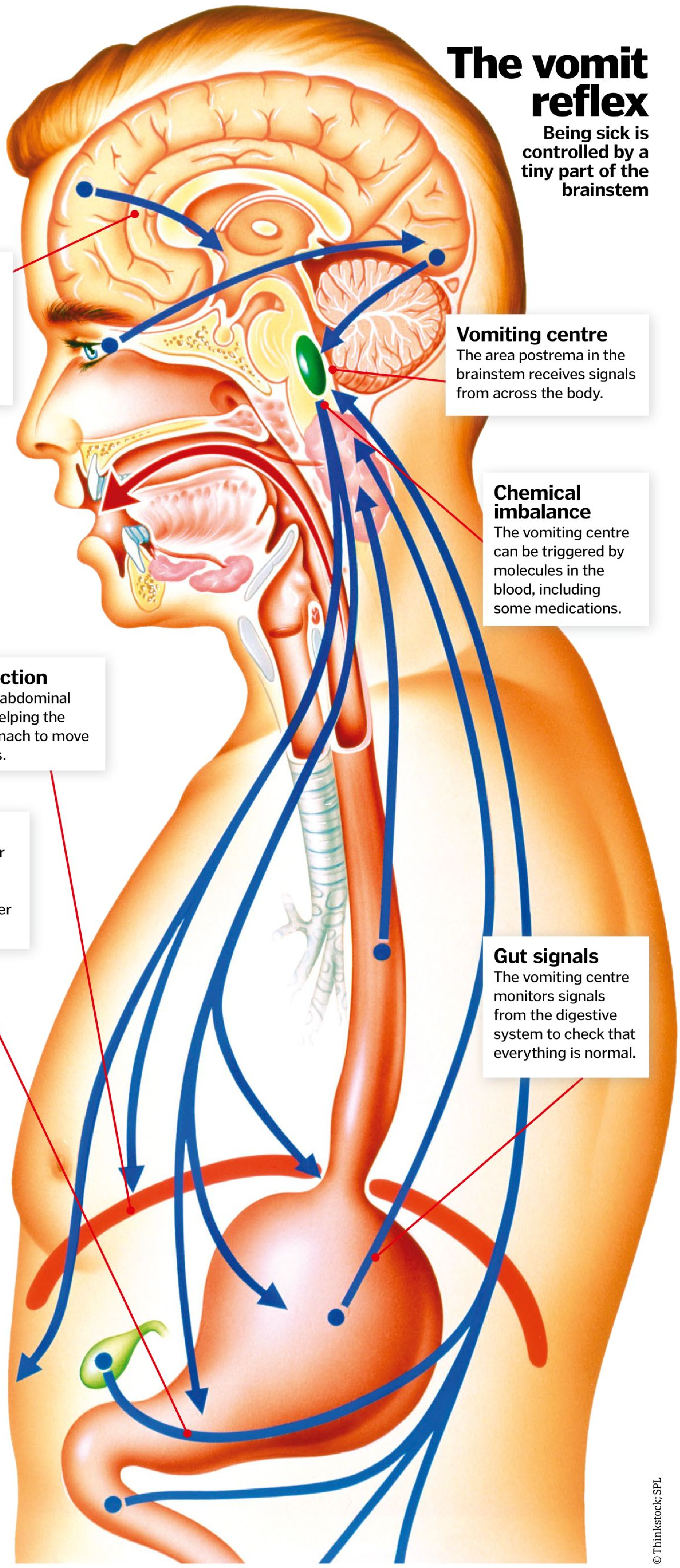
The diaphragm then contracts downwards sharply, lowering the pressure in the chest. The top of the small intestine squeezes in reverse, and the abdominal muscles crunch inwards. The contents of the stomach are squashed up into the oesophagus, and out through the mouth.

> *"The mouth fills with saliva, shielding the teeth from the stomach acid"*

Typically, the vomit reflex is triggered in response to food poisoning or motion sickness, but it can also be brought on by intense physical exertion, taking certain medicines, or as a symptom of disease

The vomit reflex

Being sick is controlled by a tiny part of the brainstem



Psychological triggers
Sensory and emotional triggers, like motion or fear, can set off the vomit reflex.

Vomiting centre
The area postrema in the brainstem receives signals from across the body.

Chemical imbalance
The vomiting centre can be triggered by molecules in the blood, including some medications.

Muscle contraction
The diaphragm and abdominal muscles contract, helping the contents of the stomach to move into the oesophagus.

Openings
The pyloric sphincter at the bottom of the stomach relaxes to allow content to enter from the gut.

Gut signals
The vomiting centre monitors signals from the digestive system to check that everything is normal.

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How wounds heal

It takes an army of cells to repair cuts and scrapes

Wound healing happens in four key stages: haemostasis, inflammation, proliferation and remodelling. Haemostasis means 'blood halting' in Greek, and is the first crucial part in closing a wound. The body's first line of defence is to constrict the blood vessels in the affected area to minimise blood loss. Platelets then start to stick to the exposed tissue, becoming activated and encouraging more and more platelets to clump together to plug the gap.

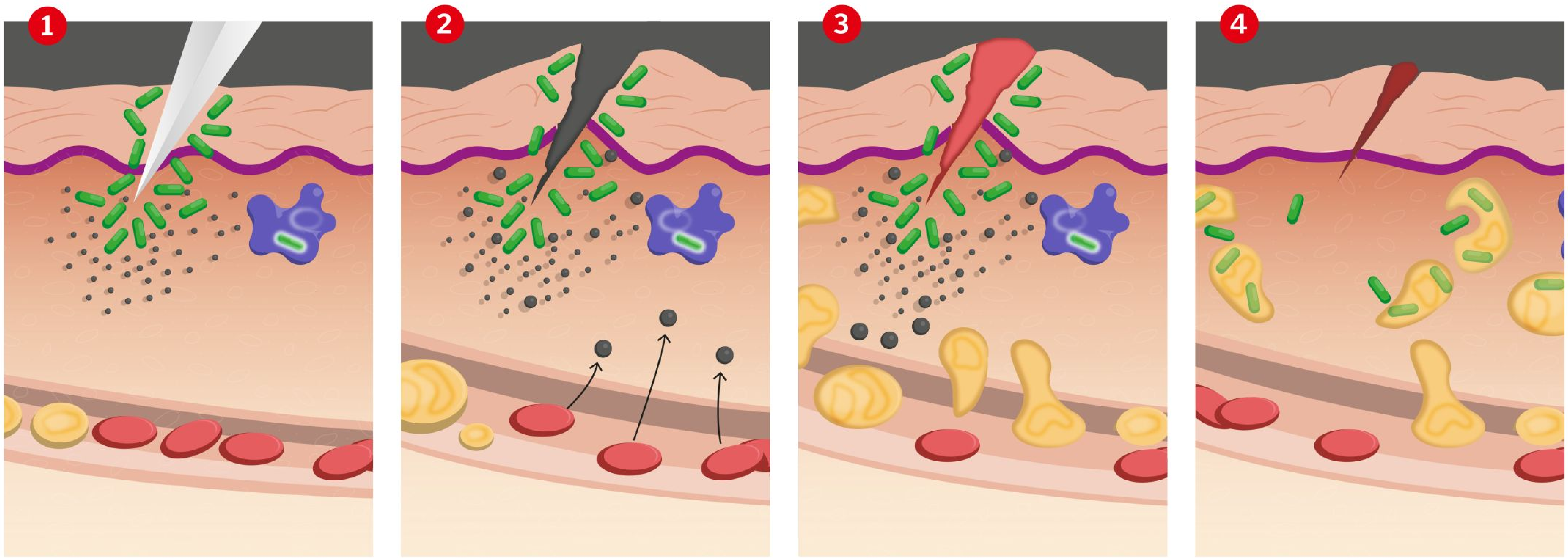
Once this plug is in place, a mesh of fibrin fibres starts to form around it, trapping passing blood cells and forming a sturdy clot that holds the wound closed until it can be repaired. This process only takes a matter of minutes, and once the bleeding stops, the local blood vessels dilate again, allowing immune cells to reach the area and begin the necessary repairs. This stage is called inflammation.

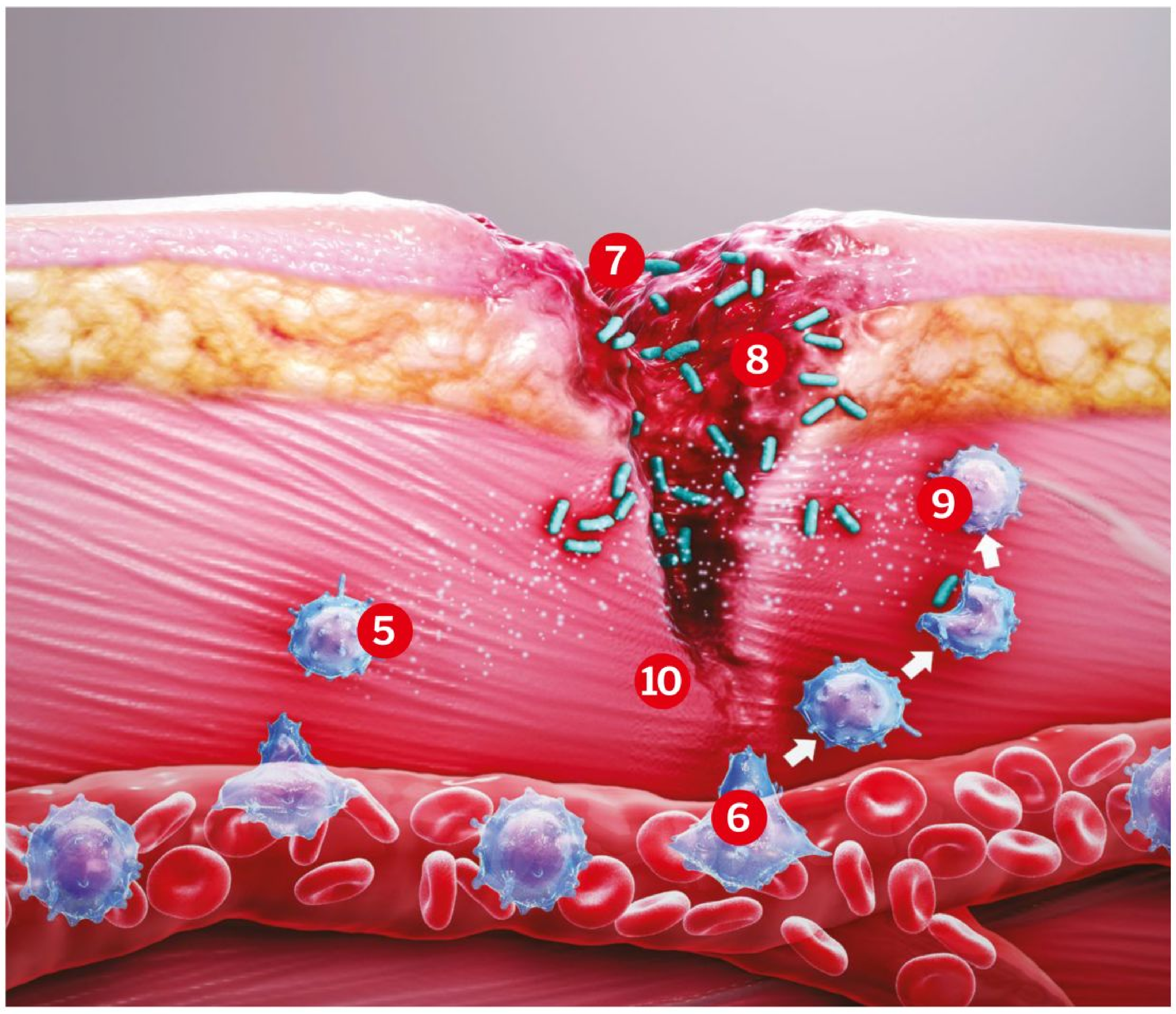
White blood cells clear up dead cells, get rid of damaged tissue and chase down any pathogens that have entered through the wound and destroy them by phagocytosis (ingesting them). They also prepare the area for the repair phase, which is known as proliferation.

With the encouragement of the immune system, long, spindle-shaped cells called fibroblasts start rebuilding the collagen scaffolding that holds healthy tissue together. On top of the wound, epithelial cells begin dividing and migrating to cover the gap. New blood vessels start to form and, as the tissue heals, myofibroblasts tug at the edges of the wound to close the hole. Once this stage is complete, it's time for remodelling. The scaffolding built by the fibroblasts is rearranged, and any unneeded cells that were made during the healing process are safely removed.

Halting infection

The immune system rushes in to prevent pathogens entering through an open wound





1. Injury
Blood vessels in the local area instantly constrict, reducing blood loss and limiting the chances of anything entering the bloodstream.

2. Clotting
A plug of platelets starts to form. Clotting factors transform it into a strong network of fibres and trapped blood cells, barricading the breach.

3. Immune response
Immune cells flood into the area, chasing down and killing any bacteria and cleaning away dead cells and damaged tissue.

4. Repair
Immune cells encourage other cells to begin repairs. The support network under the skin is regenerated, and new cells grow over the wound.

5. Macrophage
Macrophage means 'big eater'. These cells are responsible for clearing away pathogens and debris.

6. Immune arrival
Immune cells squeeze out of the blood vessels and into the tissue in a process called extravasation.

7. Granulation
New tissue starts to form at the site of the injury, disordered at first before gradually becoming orderly.

8. Bacteria
An open wound allows pathogens like bacteria to get inside the body.

9. Following the trails
Immune cells are attracted to the site of the wound by a trail of chemical signals.

10. Scarring
If the dermis (deep layer of skin) has been damaged, new collagen fibres form to mend it, creating a scar.

© SPL; Illustration by Ed Crooks

Are viruses alive?

Are these biological hitchhikers a lifeform?

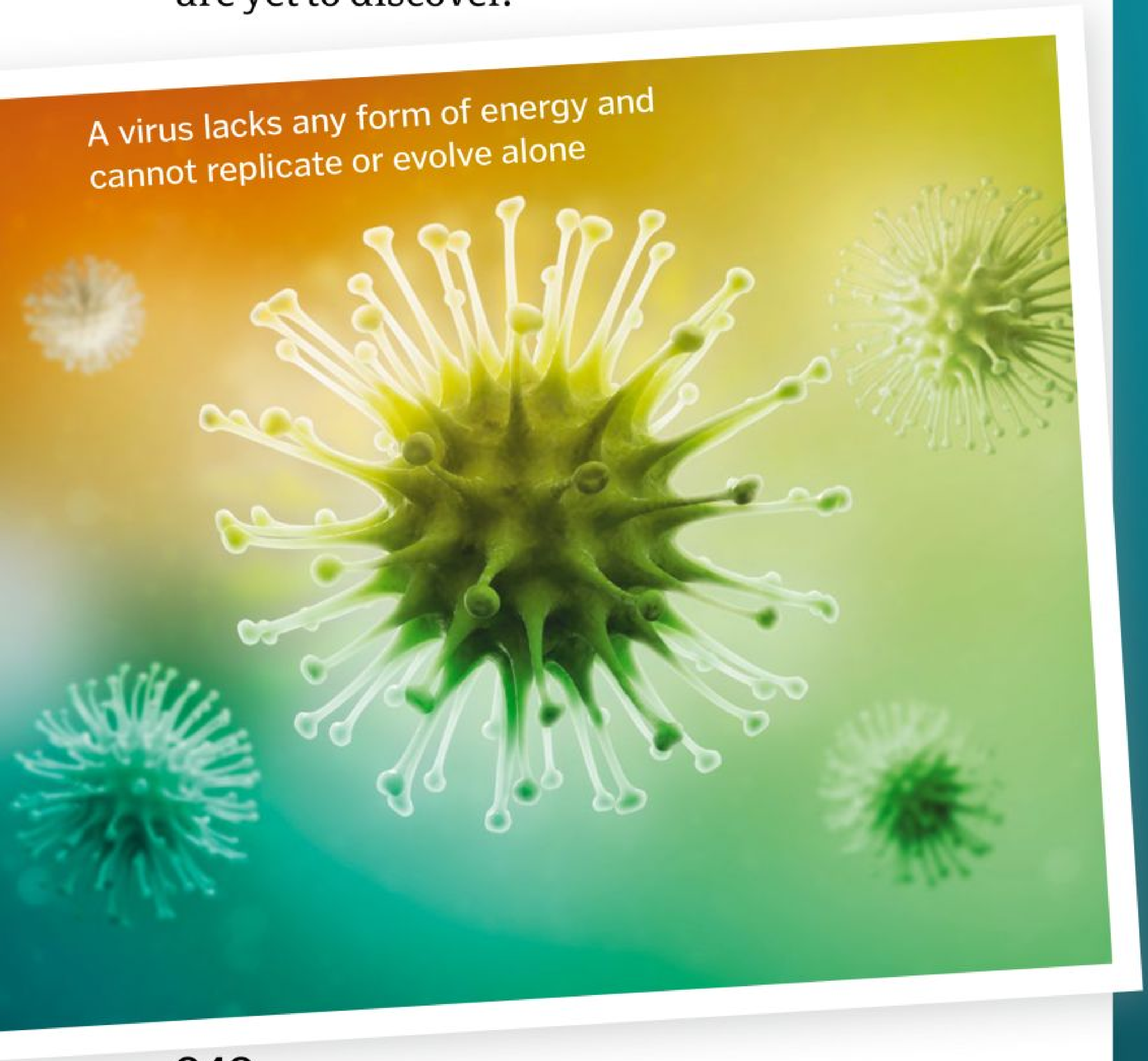
The first virus to be discovered was the Tobacco mosaic virus in 1892 and the controversy surrounding their classification as living or not living has been debated ever since.

The debate centres around the fact that viruses cannot survive without a host and they are unable to carry out even the most simple of biological processes alone. However, with a host they are able to function and reproduce like any other life form. This is because a virus is essentially an isolated free roaming string of DNA without its own cell or metabolic processes, so it has no cell of its own or the enzymes that are needed for chemical reactions such as the steps required to gain energy.

The string of nucleic acid is generally only between three to 400 genes long, and to survive it needs a host to produce and carry out the chemical reactions required to live.

Once a virus reaches a cell it is able to get inside and hitch a ride with the DNA of the host. It then combines with the DNA of the host and use it to sustain itself. Viruses can reproduce here using the cells' code for building new copies. It will then burst out of the cell when it becomes packed with replicated viruses.

For now, most scientists support the theory that viruses cannot constitute as being alive. However, it is agreed that if they are classified as life then they are the simplest form of it that we are yet to discover.



A virus lacks any form of energy and cannot replicate or evolve alone

The diving reflex

Your body's reaction to prevent you from drowning

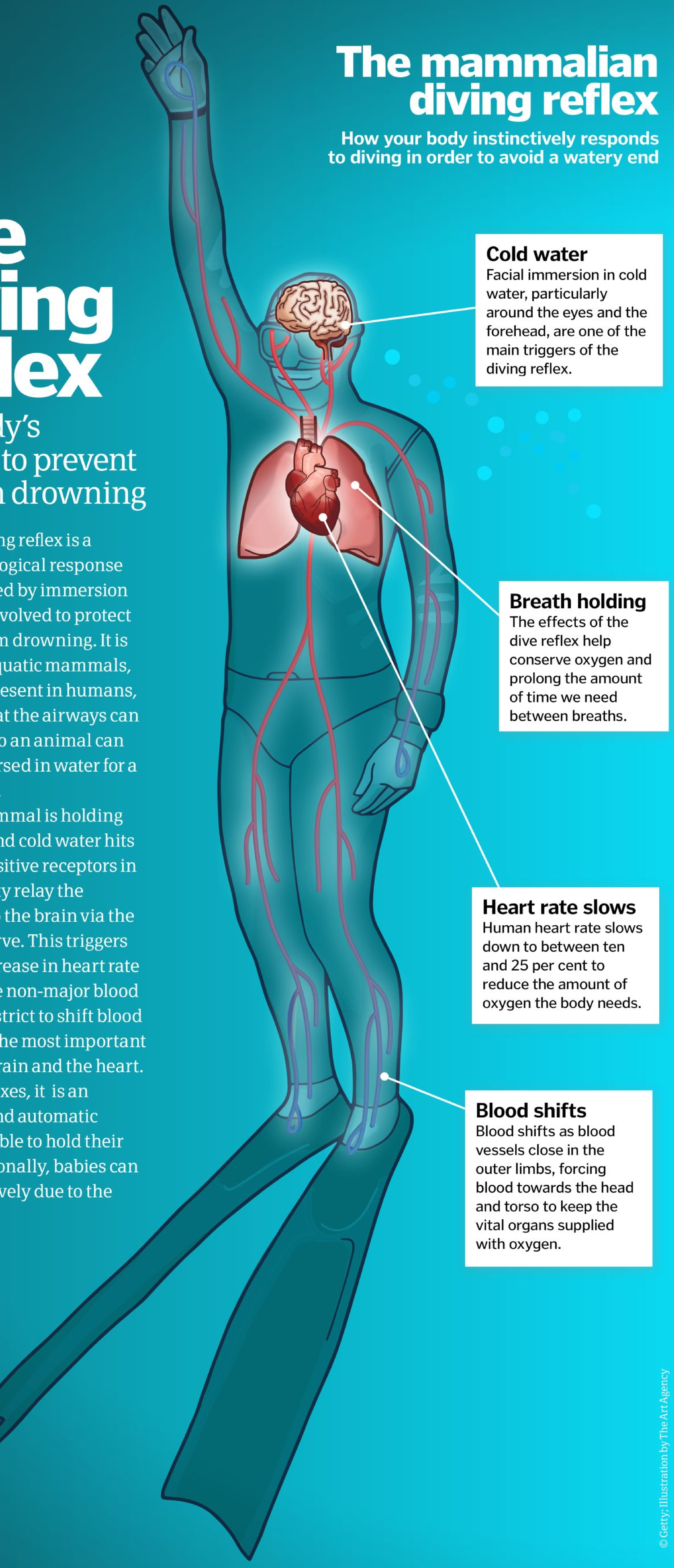
The diving reflex is a physiological response triggered by immersion in water that evolved to protect mammals from drowning. It is strongest in aquatic mammals, but it is also present in humans, and means that the airways can be protected so an animal can survive immersed in water for a period of time.

When a mammal is holding their breath and cold water hits their face, sensitive receptors in the nasal cavity relay the information to the brain via the trigeminal nerve. This triggers an abrupt decrease in heart rate and causes the non-major blood vessels to constrict to shift blood flow towards the most important organs – the brain and the heart.

Like all reflexes, it is an involuntary and automatic response. Unable to hold their breath intentionally, babies can do so instinctively due to the diving reflex.

The mammalian diving reflex

How your body instinctively responds to diving in order to avoid a watery end



Cold water
Facial immersion in cold water, particularly around the eyes and the forehead, are one of the main triggers of the diving reflex.

Breath holding
The effects of the dive reflex help conserve oxygen and prolong the amount of time we need between breaths.

Heart rate slows
Human heart rate slows down to between ten and 25 per cent to reduce the amount of oxygen the body needs.

Blood shifts
Blood shifts as blood vessels close in the outer limbs, forcing blood towards the head and torso to keep the vital organs supplied with oxygen.

© Getty; Illustration by The Art Agency

Photosynthesis

Our quick-fire guide to how plants capture energy from the Sun

Photosynthesis in action

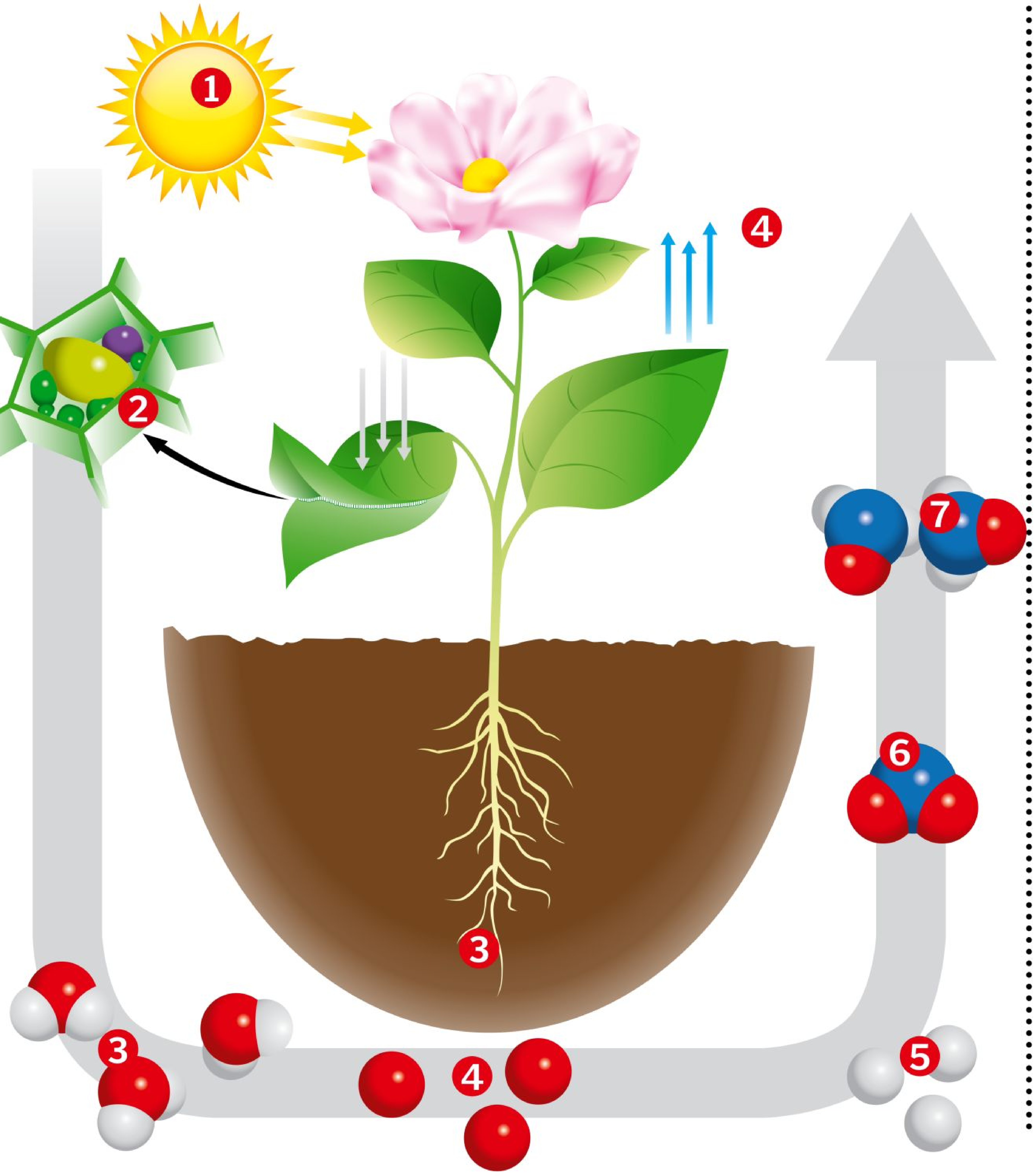
This simple process keeps life on Earth supplied with energy

Sunlight streams onto the Earth's surface every day, supplying an estimated 175 watts of power for every square metre of our planet. Most of this light is reflected, absorbed or scattered, but some of it is captured by green plants, phytoplankton and cyanobacteria. These organisms then use it to create the building blocks of life, powering almost every living thing in our world.

Using the Sun's energy, these organisms transform carbon dioxide and water into a sugar called glucose, which is then used for respiration. Oxygen is a by-product of this process, which is known as photosynthesis.

Cells capable of transforming carbon dioxide and water into sugar and oxygen are known as photosynthetic. They contain pigments that absorb light; when the Sun shines, electrons inside the pigments become excited and break away from their atoms. The cells then shunt these through an 'electron transport chain', storing their energy in molecules called ATP and NADPH. This energy is then used to build sugar molecules. In order to keep the system running, the electrons are replaced by splitting water molecules, creating oxygen in the process.

The most well-known pigment is chlorophyll A, which absorbs red and blue light and reflects green, giving plants their familiar hue.



1 Sunlight
Light from the Sun strikes the plant's leaves, hitting the cells inside.

2 Chlorophyll
Certain cells contain chlorophyll, and as the sunlight strikes, electrons become excited.

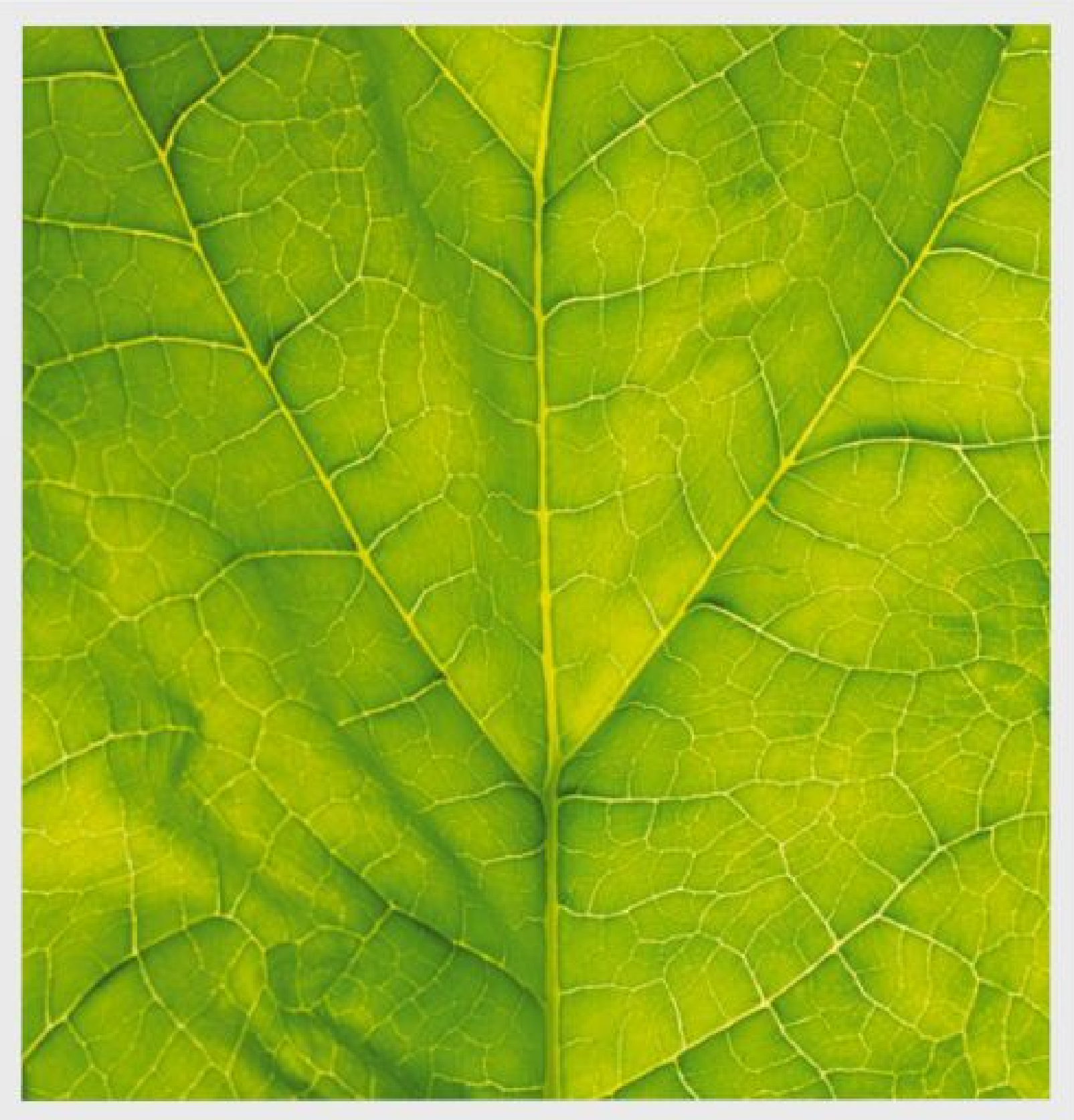
3 Water
The plant takes in water and splits the molecules into oxygen, electrons and hydrogen ions.

4 Oxygen
The oxygen can either be used by the plant, or released into the air.

5 Hydrogen
The hydrogen atoms are saved to be used in building sugar molecules in the next stage.

6 Carbon dioxide
The plants take in carbon dioxide and, using the energy they have trapped from the sunlight, they combine it with hydrogen.

7 Sugar
The result is brand-new sugar molecules, which can be used for energy or as the building blocks for making starch.



Limiting factors

The speed of the photosynthesis process is affected by three key factors: the amount of light, the amount of carbon dioxide and the temperature.

If there is too little of either of the key ingredients – light and carbon dioxide – then the inevitably photosynthesis slows down. If the Sun is too bright and too much light reaches the leaves, the pigments of the leaf can become damaged.

Capturing light from the Sun doesn't rely purely on temperature, but using the stored energy to build sugar molecules does. This part of the process is done by molecular machines that we know as enzymes. If it is too cold, the enzymes can't move fast enough to perform the reactions, and if it is too hot, they can become bent out of shape.

Plants also need magnesium. It is used to make chlorophyll, and without it the leaves of the plant turn yellow and photosynthesis slows again.

The human BRAIN

Described as the most complex thing in the universe, our brains are truly astonishing

The brain makes up just two per cent of our total body weight, but crammed inside are approximately 86 billion neurons, surrounded by 180,000 kilometres of insulated fibres connected at 100 trillion synapses. It's a vast biological supercomputer.

The cells in the brain communicate using electrical signals. When a message is sent, thousands of microscopic channels open, allowing positively charged ions to flood across the membrane. Afterwards, more than 1 million miniature pumps in each cell move the ions back again ready for the next impulse.

The cell bodies of the neurons, and their connections, are contained within the grey matter, which consumes 94 per cent of the oxygen delivered to the brain. Different areas are responsible for different functions, and wiring them together is a fatty network of fibres called white matter.

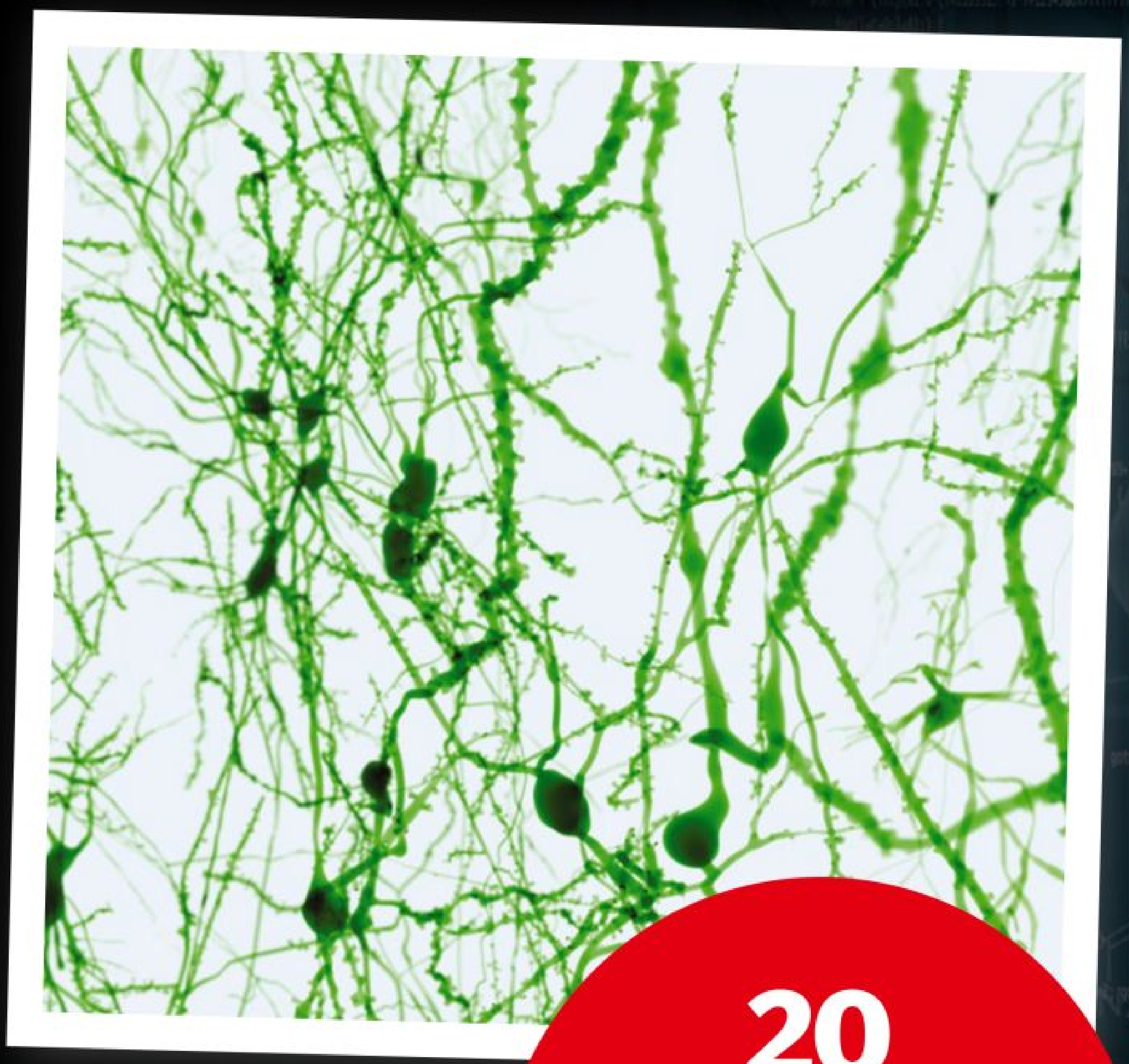
When a signal reaches the end of a nerve cell, tiny packets of chemical signals spill out onto the surrounding neurons. These connections, called synapses, allow messages to be passed from one cell to the next. Each neuron can receive thousands of inputs, coordinating them in time and space, and by type of chemical, to decide what to do next.

Scientists have been electrically and chemically stimulating the brain to see how it responds to different signals, recording electrical activity to map thoughts and using imaging like functional MRI to track the blood flow increases that reveal when nerve cells are firing. The cells of the brain can also be studied inside the lab. Thanks to these investigations we know more about this incredible structure than ever before, but our understanding is only just beginning. There is so much more to learn.

Brain development

From a single cell to an incredibly intricate network in just nine months

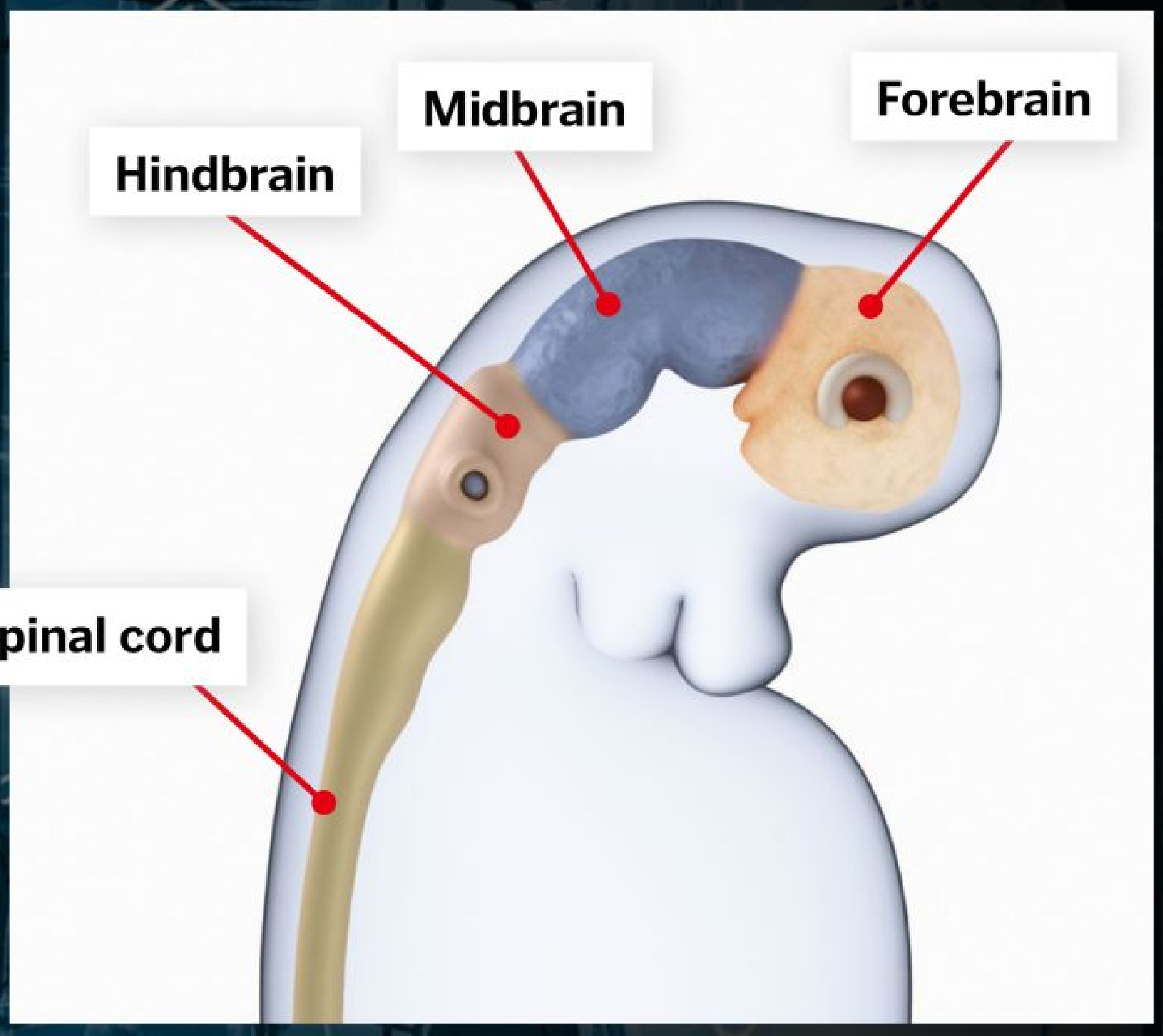
Within weeks of fertilisation, neural progenitors start to form; these stem cells will go on to become all of the cells of the central nervous system. They organise into a neural tube when the embryo is barely the size of a pen tip, and then patterning begins, laying out the structural organisation of the brain and spinal cord. At its peak growth rate, the developing brain can generate 250,000 new neurons every minute. By the time a baby is born, the process still isn't complete. But, by the age of two, the brain is 80 per cent of its adult size.



Pyramidal neurons, like these, are found in the hippocampus, cortex and amygdala

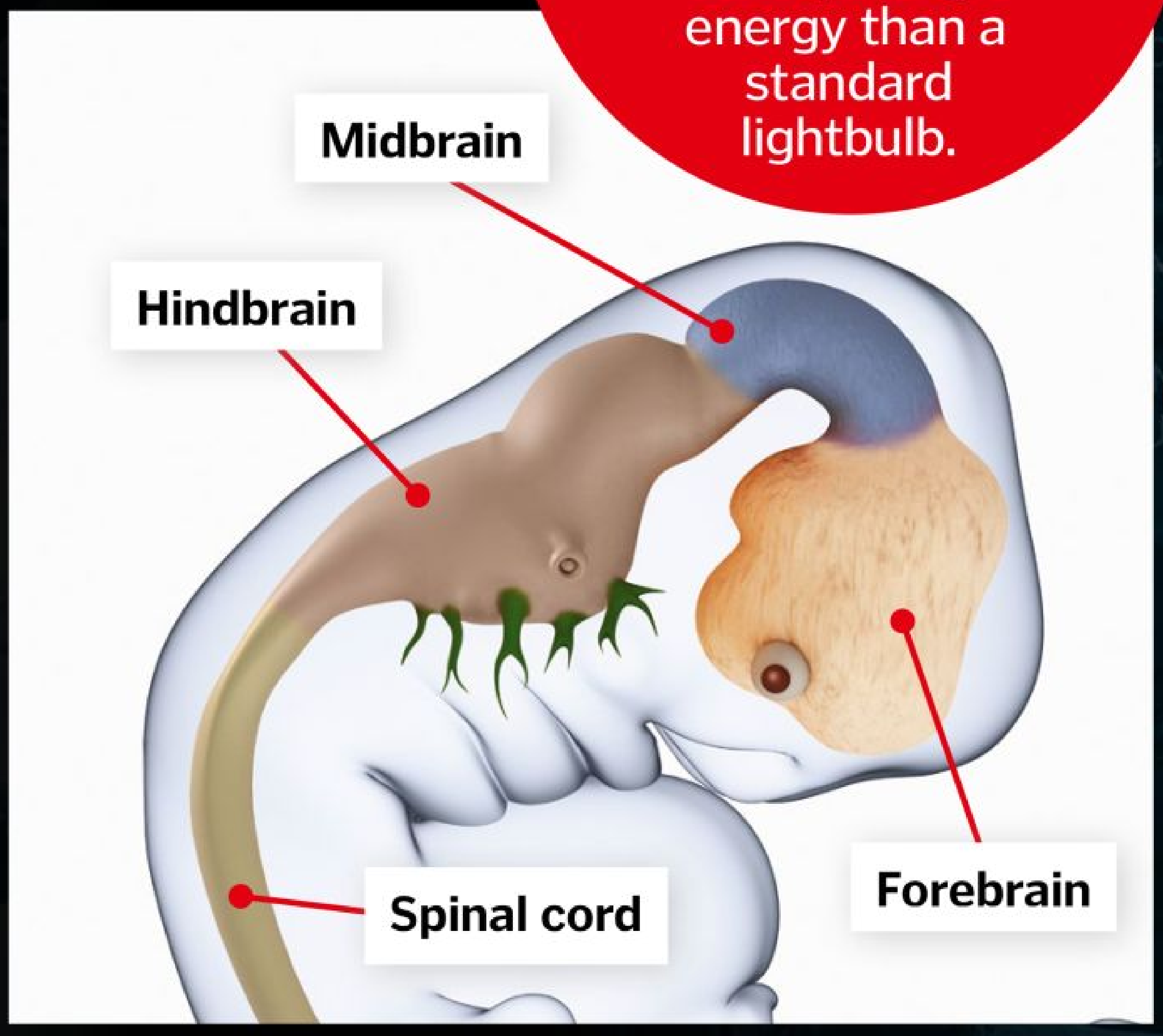
Brain formation

This astonishing structure is formed and refined as pregnancy progresses



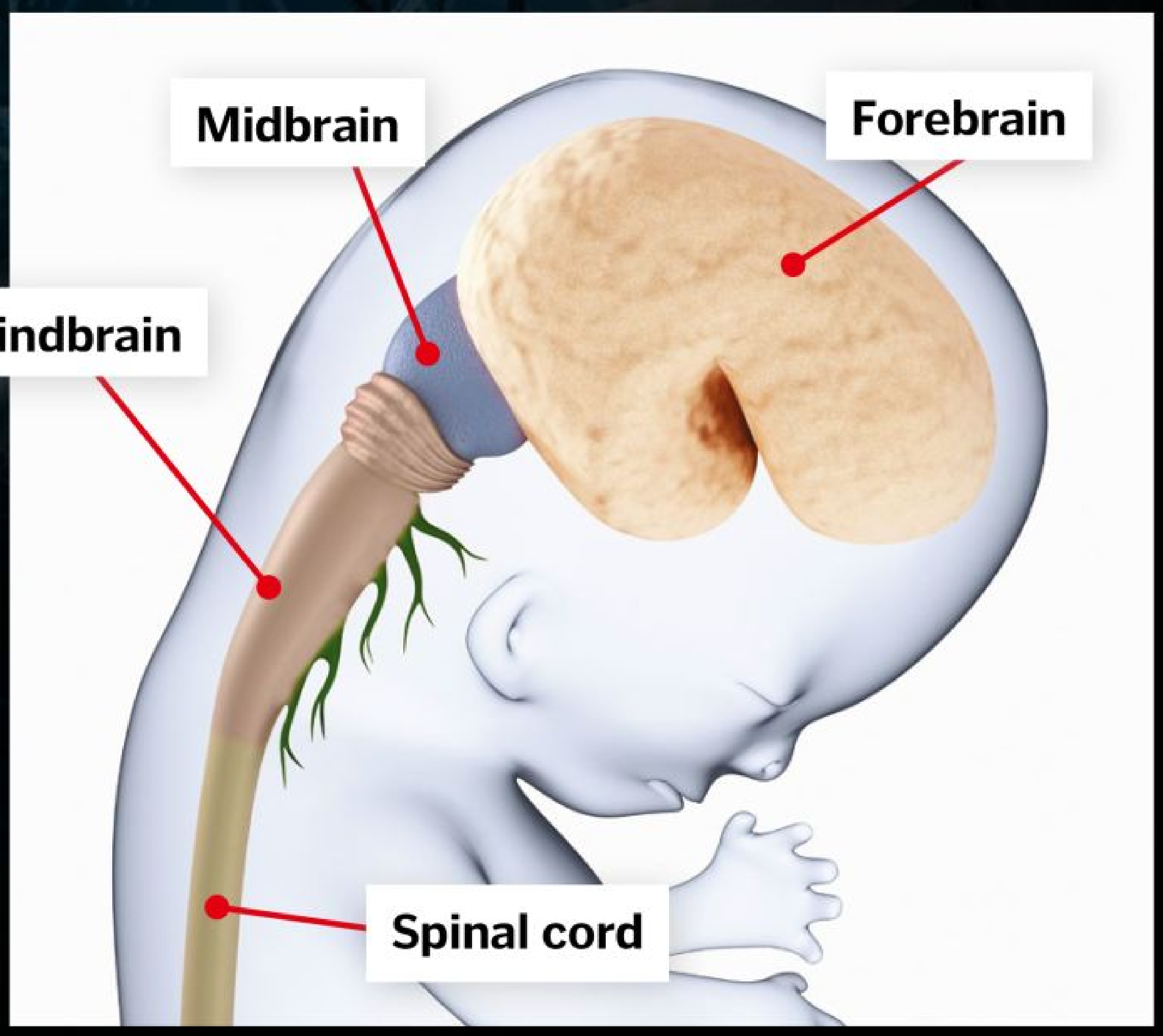
4 weeks

Brain development starts just three weeks after fertilisation. The first structure is the neural tube, which divides into regions that later become the forebrain, midbrain, hindbrain and spinal cord.



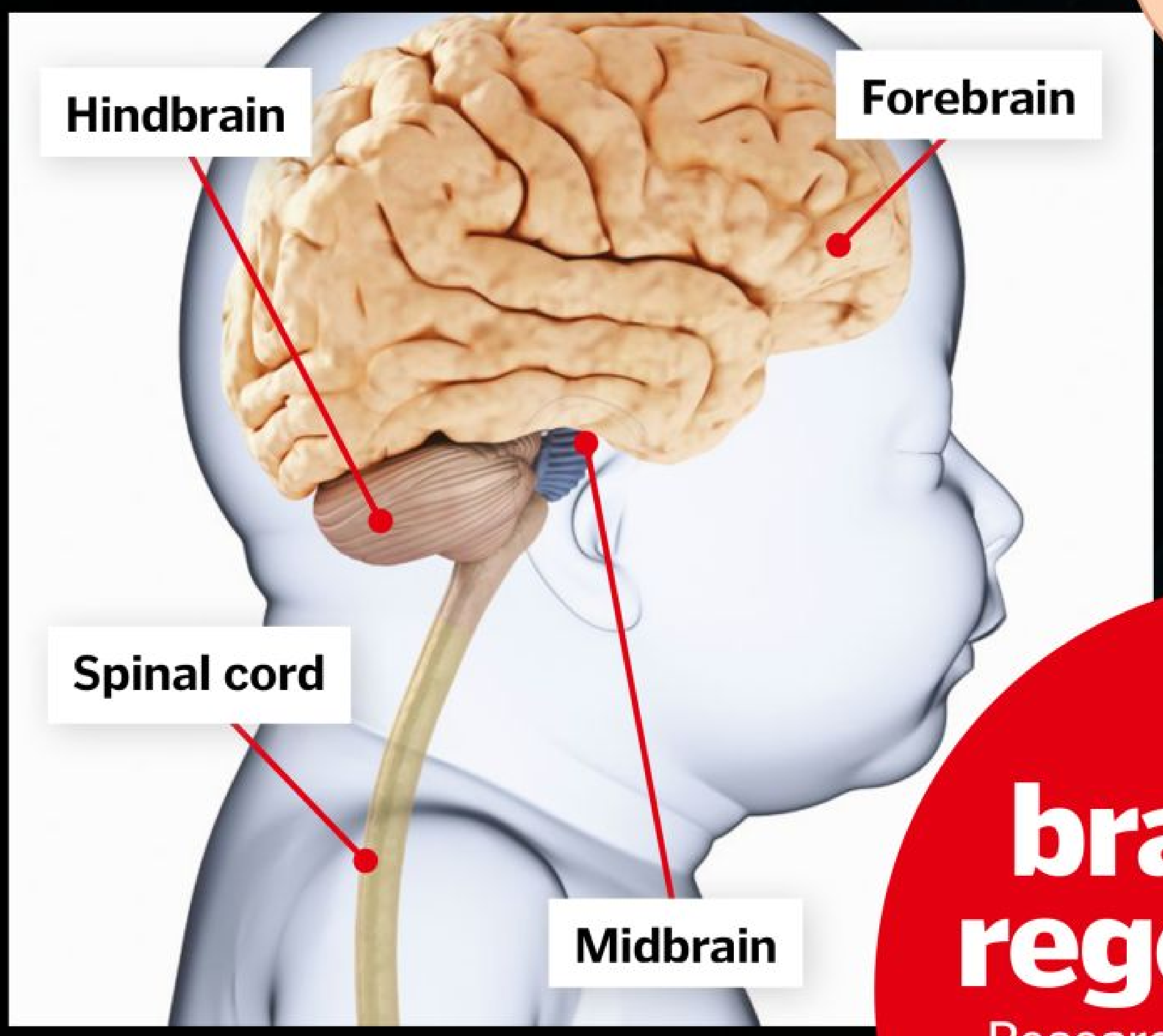
6 weeks

The pattern of the brain and spinal cord is now laid out and is gradually refined, controlled by gradients of signalling molecules that assign different areas for different functions.



11 weeks

As the embryo becomes larger, the brain continues to increase in size and neurons migrate and organise. The surface of the brain gradually begins to fold. At this point, a foetus only measures about five centimetres in length.



Birth

Before a baby is born, around half of the nerve cells in the brain are lost and connections are pruned, leaving only the most useful. This process continues after birth.

20 watts

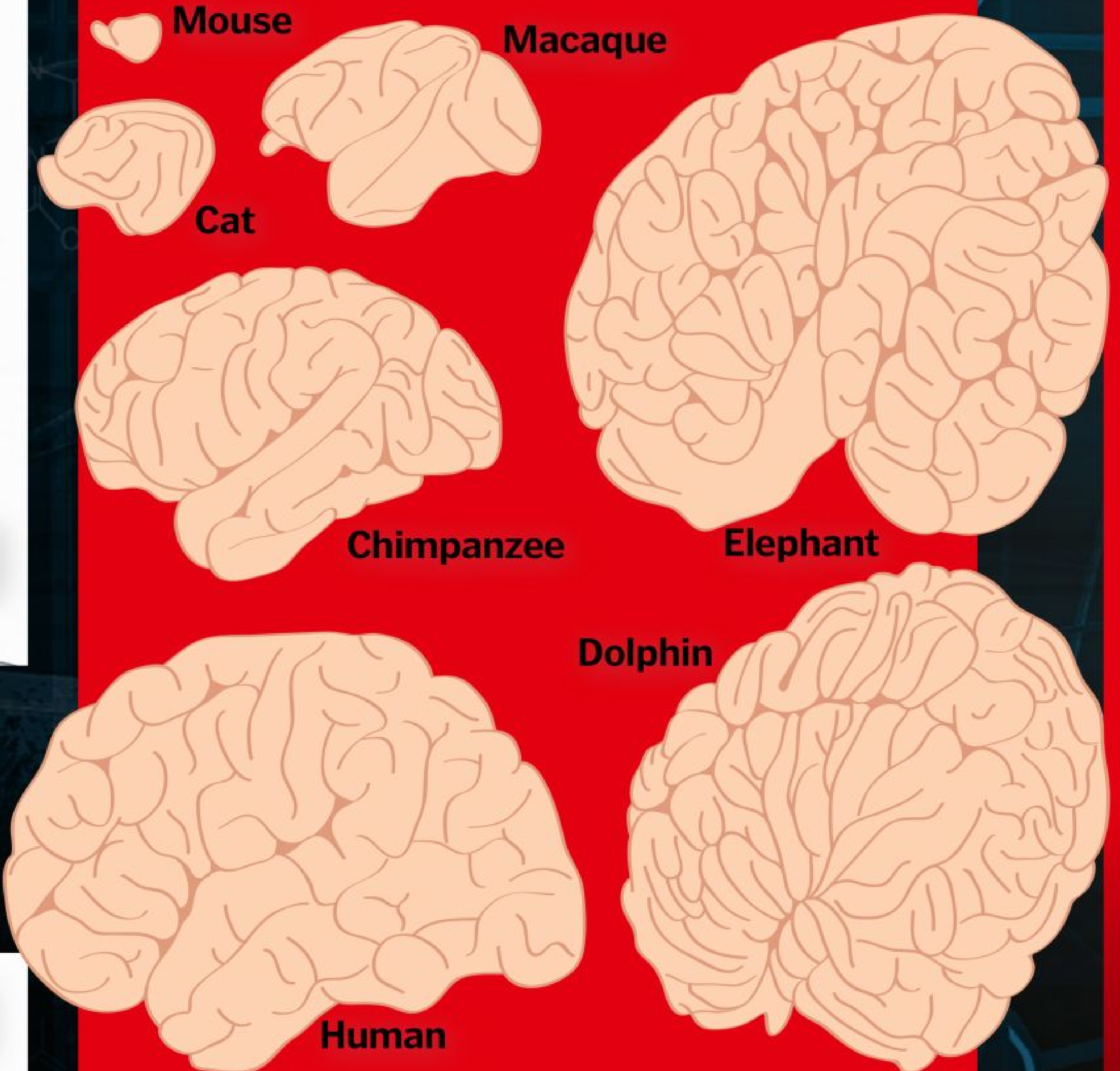
Your brain is incredibly efficient, using less energy than a standard lightbulb.

Why the brain is wrinkled

The brain folds in on itself to cram in more processing power

The folds and pockets of our brains are a biological rarity that we only share with a few other species, including dolphins, some primates and elephants. It's a clever evolutionary adaptation that allows intelligent species to squash a huge amount of cortical tissue into a small space, allowing enormous brainpower to be crammed into our relatively small skulls.

Folding starts during the second trimester of pregnancy, creating ridges (gyri) and fissures (sulci), but the biology behind the distinctive wrinkles is stranger than you might think. The organisation of the brain is determined by complex cascades of chemical signals, but the overall shape seems to be the result of simple physics. Grey matter sits on the outside of the brain and, during development, its growth rapidly outpaces the growth of white matter underneath. This puts mechanical stress on the structure, forcing the outside to buckle and curl.



More wrinkled brains are associated with higher intelligence (brain sizes not to scale)

The brain can regenerate

Research has shown that certain areas of the adult brain can continue to produce new neurons, a process known as neurogenesis.

> "Our brains contain 86 billion neurons and 180,000 kilometres of fibres"

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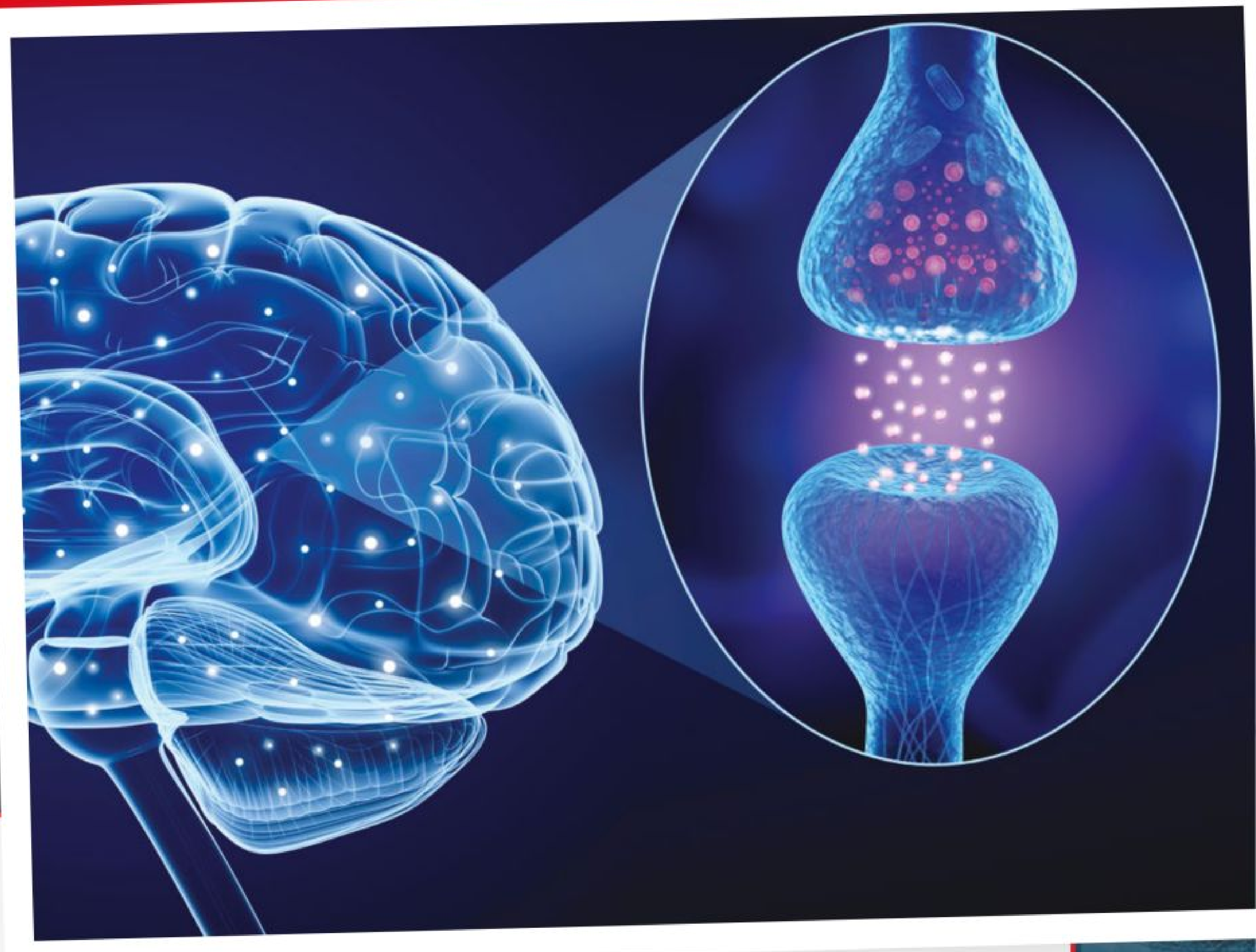
Making memories

The brain can store around 1 million gigabytes of data

A team at the Salk Institute in California estimate that the brain can store around 1 petabyte of information, stuffed into the connections between nerve cells. That's around 2,000 years worth of MP3 music or 223,000 DVDs. And, incredibly, it's possible to watch memories being made.

The Weizmann Institute in Israel and UCLA in the US captured memory formation in action. Patients watched clips of videos and were then asked to recall what they'd seen. The neurons that lit up when they watched the first time lit up again as they relived the experience inside their heads – a bit like an echo.

Recent research from the US and Japan suggests that these echoes are actually stored twice in our brains – once in the hippocampus and again in the cortex. The hippocampus handles short-term storage and gradually forgets, but as it does so, it helps to reinforce the memory in the cortex, allowing for long-term recall.



Neurons make new connections when a memory is formed

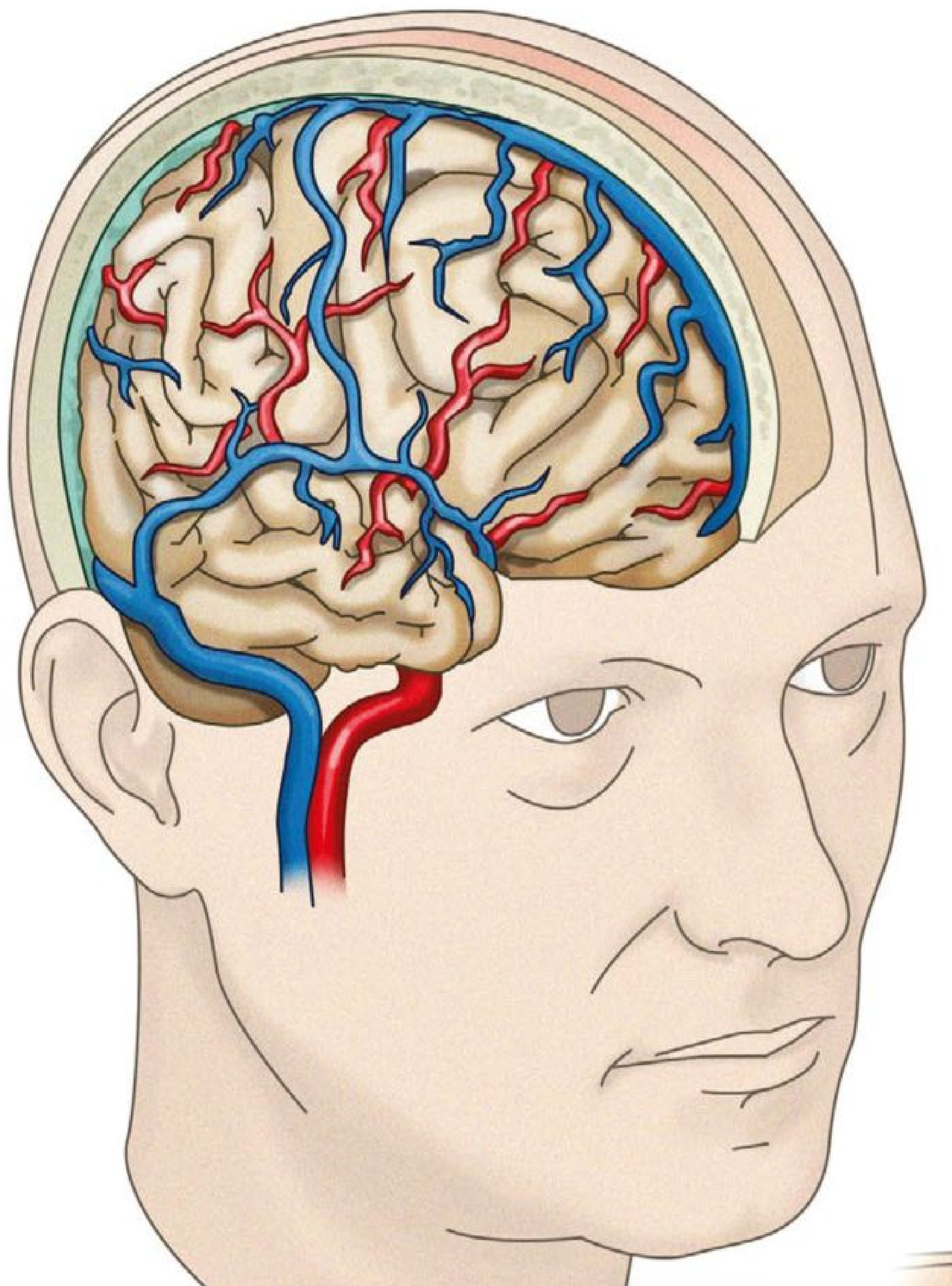
Self-cleaning brains

We have a built-in system to clear toxic waste from between our brain cells

Sleep is one of the brain's great mysteries, but research on mice has revealed an intriguing night time cleanup system. The brain is shielded by a barrier made and maintained by cells called astrocytes. They hug the blood vessels, controlling what's allowed in and out, and a space between the vessel wall and these cells seems to play a crucial role in keeping the brain clean.

At night, the astrocytes relax their grip and the space fills up with a clear liquid called cerebrospinal fluid (CSF). It's pushed along by the movement of the blood vessels underneath, swishing up through the astrocytes and out into the spaces between brain cells. As it passes, it picks up waste and debris, carrying the particles back towards the bloodstream so that they can be removed from the brain.

> *"The brain is shielded by a barrier made and maintained by cells called astrocytes"*

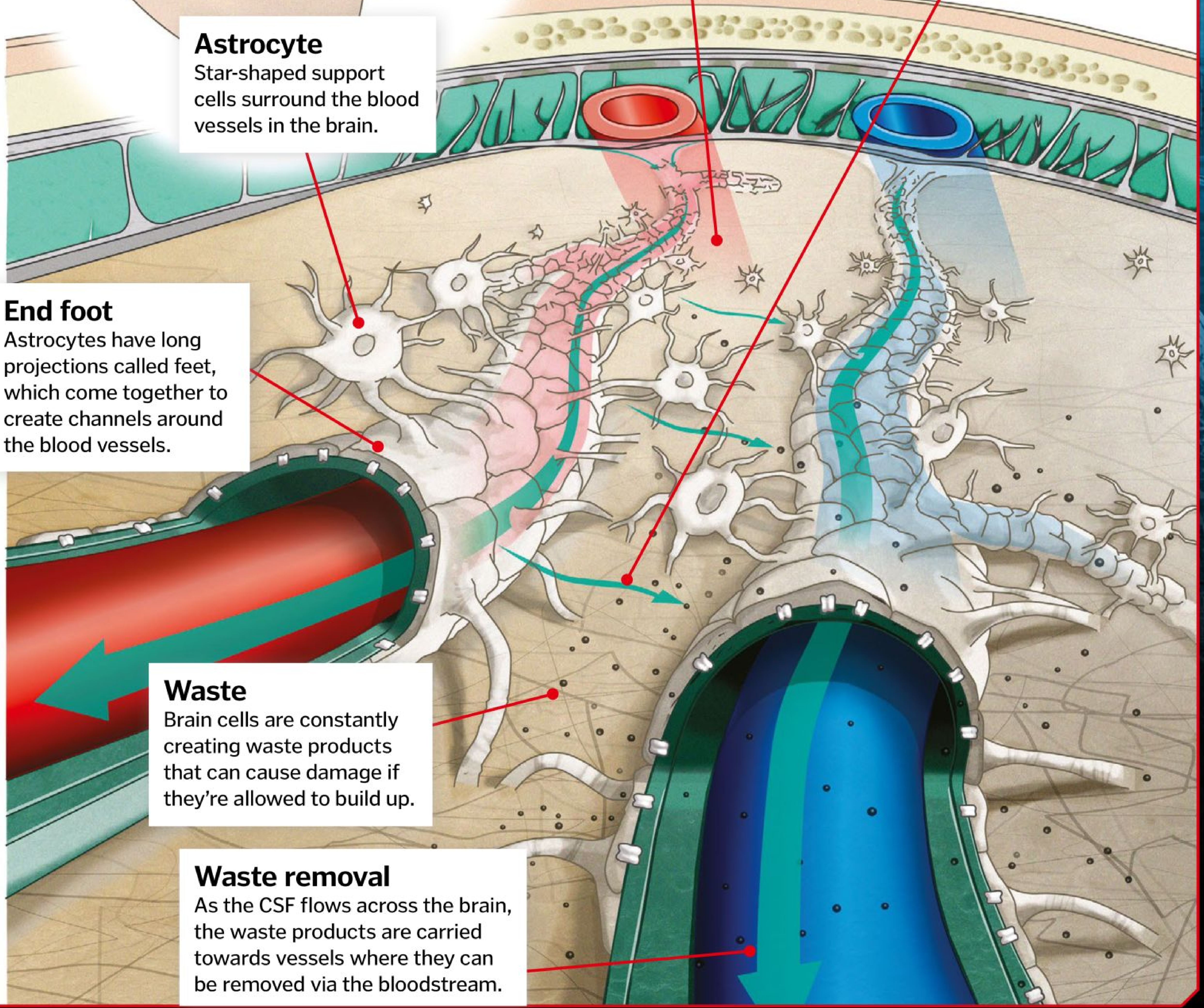


The cleaning process

CSF sweeps away the dirt of the day as we sleep

Cerebrospinal fluid (CSF)
The brain is bathed in clear liquid that carries nutrients in and waste products out.

Flow
At night, the channels around the blood vessels widen, allowing CSF to sweep through the brain.



Astrocyte
Star-shaped support cells surround the blood vessels in the brain.

End foot
Astrocytes have long projections called feet, which come together to create channels around the blood vessels.

Waste
Brain cells are constantly creating waste products that can cause damage if they're allowed to build up.

Waste removal
As the CSF flows across the brain, the waste products are carried towards vessels where they can be removed via the bloodstream.

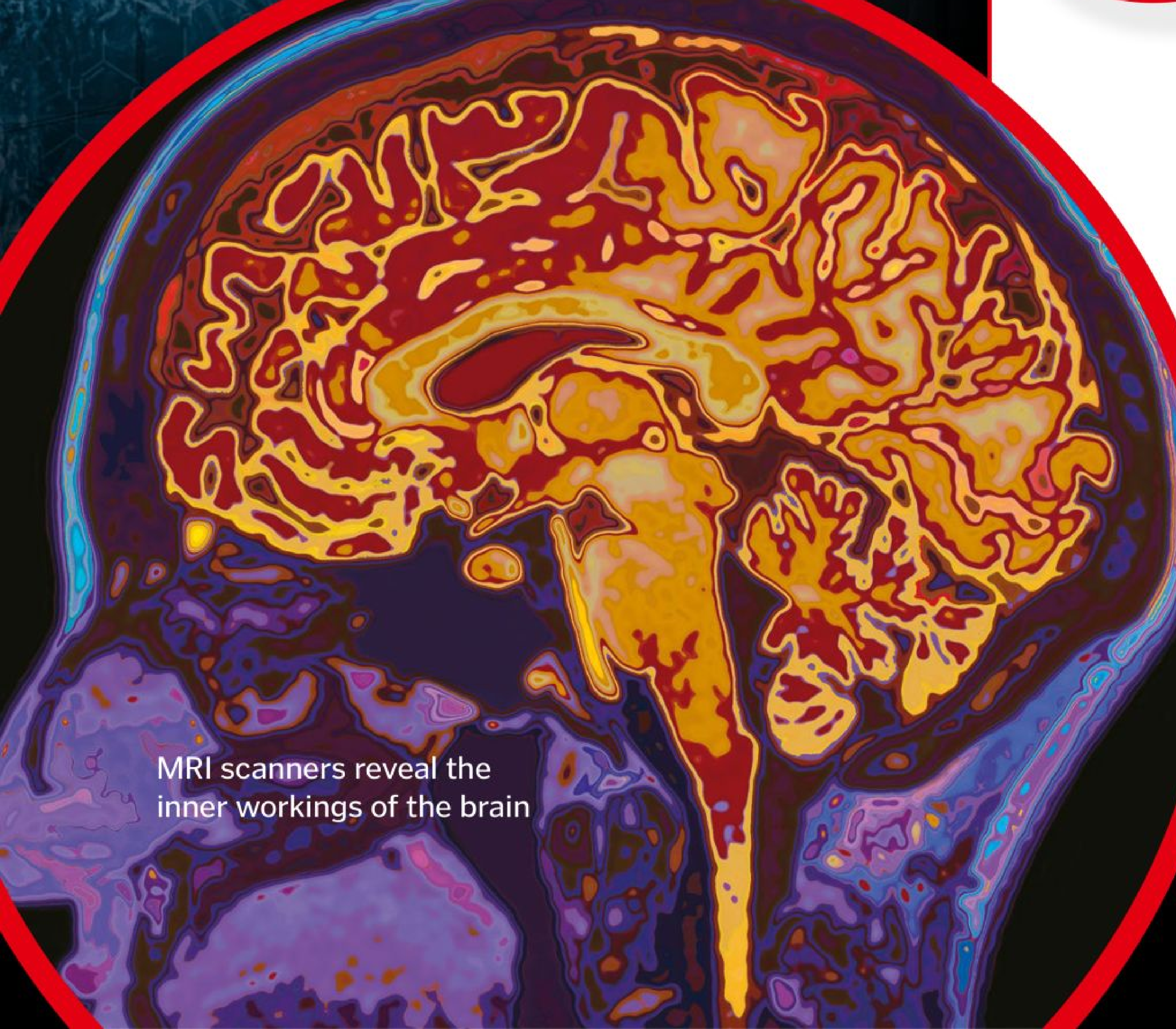
Electrodes can detect the electrical signals produced by our brains

Mind reading

Thoughts are electricity, and that means that they can be detected and decoded

Electrodes placed on the scalp can listen out for signals made by the buzzing of neurons inside the brain, and researchers are developing ways to decode the messages. It works by using a computer that can learn the patterns that the brain creates when people focus on a single, simple thought, like a movement or a word. The signals can then be used to control a prosthetic, command a computer, or they can even be sent to someone else's brain using magnets placed across their scalp.

It might sound like science fiction, but this field is moving so quickly that even big companies like Facebook want in on the action. In 2017, Mark Zuckerberg announced that the company are "working on a system that will let you type straight from your brain about five-times faster than you can type on your phone". They're also working on a skin sensor that can translate touch into thoughts, mimicking what the ear does with sound.



MRI scanners reveal the inner workings of the brain

Mind over matter

Sheer brainpower drives the healing impact of the placebo effect

Placebos are an important part of testing new treatments. Before new medicines or procedures hit the clinic, they are compared to a pill, patch or injection that doesn't contain any active ingredients. Neither the doctor nor the patient know which is which, helping to prevent bias. But the brain is a powerful thing, and just thinking you're getting treatment can make you feel better – or give you side-effects.

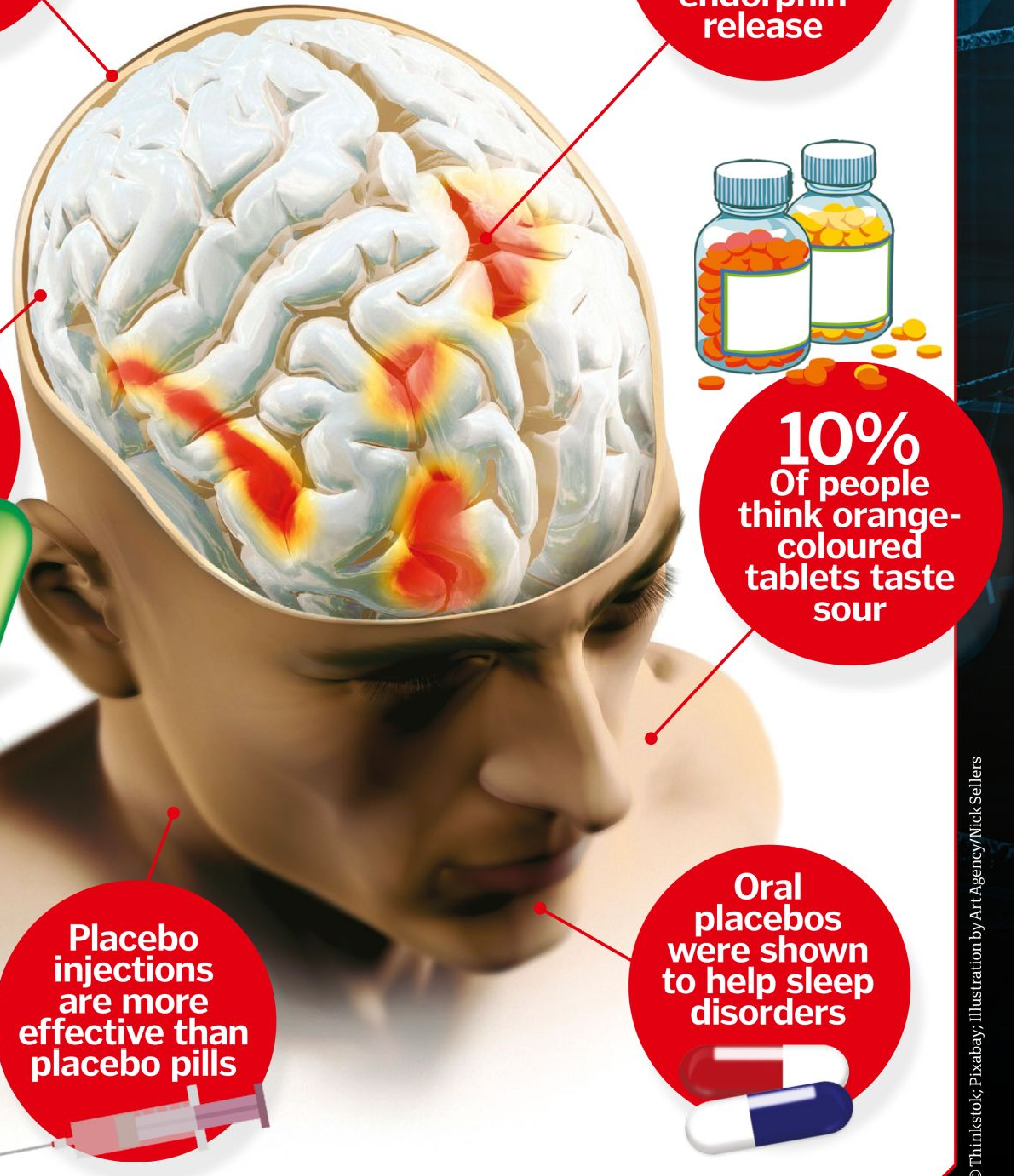
One of the most famous studies, led by Jon Levine in 1978, attempted to find out what was happening. He and his team gave placebo 'painkillers' to patients after wisdom tooth extraction. Their studies revealed that the pain relief the patients experienced was actually down to the release of their own natural painkillers – endorphins.

This strange effect can't cure cancer or get rid of asthma, but, with a little help from sugar pills and saline injections, your brain can change the way you feel.

> "Just thinking you're getting treatment can actually make you feel better"

It's all in your head

The power of the mind can do amazing things



The placebo effect works even if you're aware it's a placebo

A placebo can provide pain relief by stimulating endorphin release

Green and blue tablets are associated with a sedative effect

10% Of people think orange-coloured tablets taste sour

Placebo injections are more effective than placebo pills

Oral placebos were shown to help sleep disorders

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Genetically modified organisms

How and why do scientists manipulate genetic information?

Organisms have tens of thousands of proteins, and genetic modification is the process of them being transferred from one organism to another. Nature has done this for millennia. For example, some types of sweet potato express a gene from bacteria that introduced itself into the potato genome. Scientists then developed a way to do this intentionally.

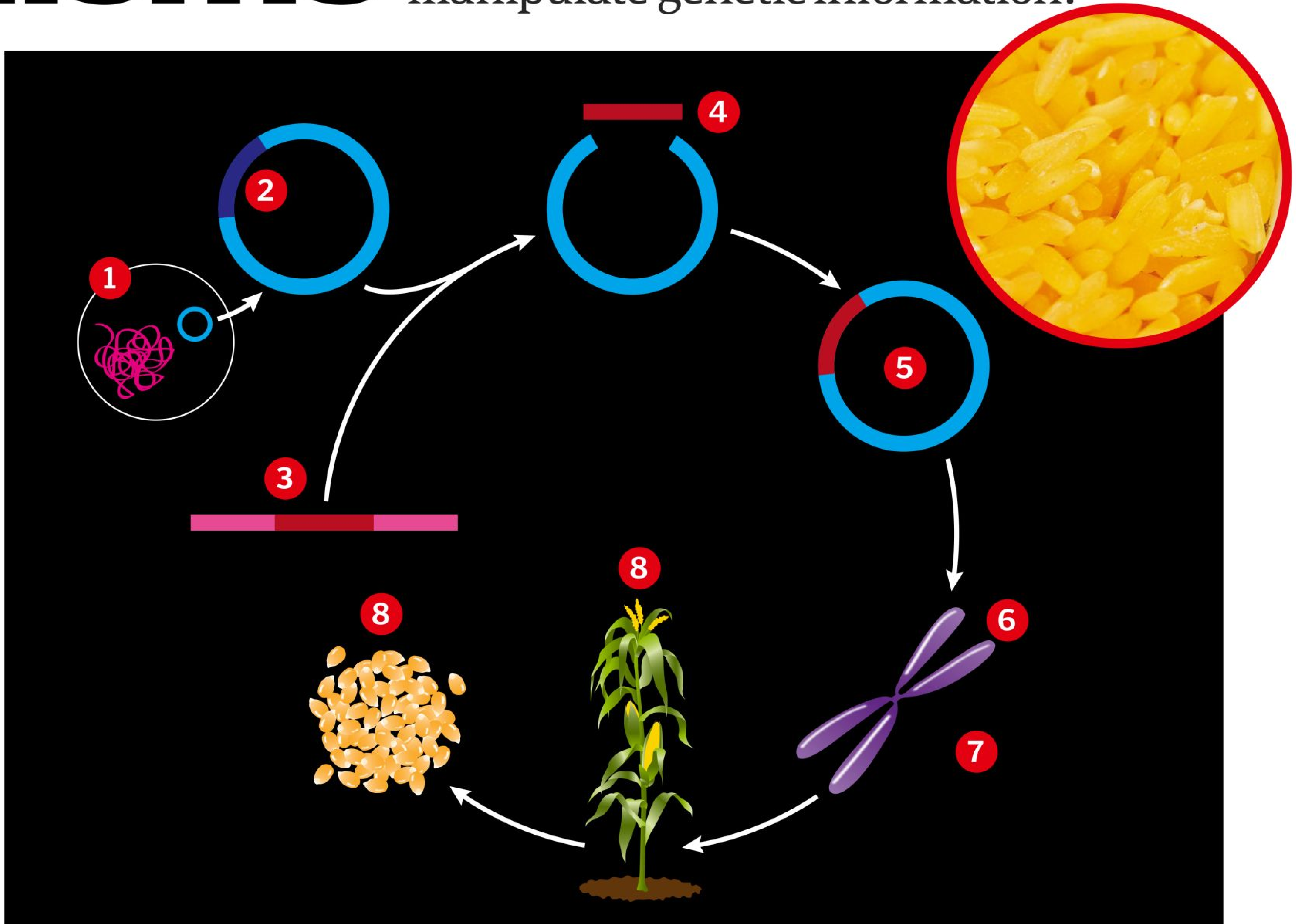
The first patent for a genetically engineered organism was a bacterium. Developed in 1971 by Ananda Chakrabarty, an Indian-American biologist, it was designed to have a taste for crude oil so that it could help clear oil spills by either absorbing the oil or breaking it up.

Scientists decide what trait they would like to introduce into an organism, such as resistance to drought or the ability to produce a vitamin. By analysing the genetic code they can identify exactly which part of the DNA codes for the gene of interest and select enzymes that will cut out the part they need. Generally, they will then alter the genome of a plant by using a bacterium called Agrobacterium tumefaciens. This bacterium naturally enters plants' cells in the wild.

A few specific genes are then removed from the bacterial plasmid, a circular genetic structure that can replicate independently and be transmitted across bacteria. This cutting leaves a linear piece of DNA that codes just for replication instructions and for cell functioning.

To create the new 'recombinant plasmid' the cut gene of interest, the linear receiving DNA and the enzyme DNA ligase are all mixed together, causing the integration of the new gene.

The cells are grown in culture and will produce seeds as adults, which will all inherit the transgene, though they may not express it.



1. First, the plasmid is removed by opening up the bacterial cell and purifying the contents inside.

2. T-DNA is cut from the plasmid using restriction enzymes, which slice the genome at specific points to remove some genes.

3. The foreign DNA that needs to be transferred into the T-DNA is also cut using restriction enzymes to select the target gene.

4. The cutting process creates a linear molecule that is ready to accept new DNA.

5. The gene and opened vector are mixed together with DNA ligase, an enzyme that connects the ends of the gene and open vector.

6. Heating up the cells (heatshocking) is thought to create pores that allow the engineered plasmid to enter the plant cell.

7. The bacterium carries the gene of interest and the replication instructions into the chromosomes of a plant cell wall.

8. The plant cells grow in culture and eventually produce seeds that contain the naturally inherited transgene.

GMOs matter

GMOs have the potential to reduce world hunger and malnourishment, particularly for those living in low-income countries. Examples of such innovations include 'golden rice', which is being modified to have an enhanced level of the vitamin beta-carotene.

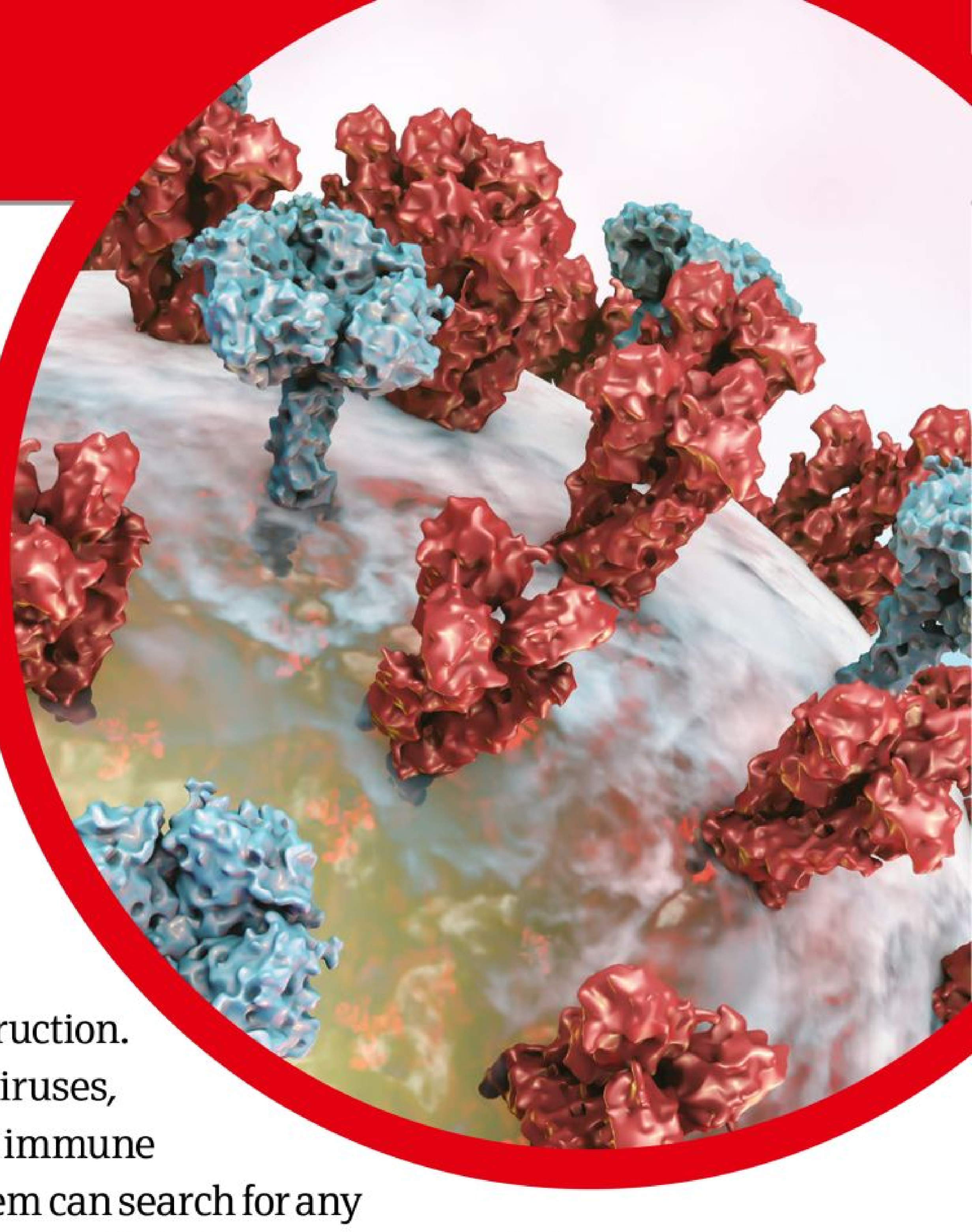
Other types of rice have also been modified by scientists so that they can survive with very limited water after having a gene from a desert plant introduced into its genome. Tomatoes that are resistant to frost and freezing temperatures have also been made using an anti-freeze gene from a cold-water fish.

In the future, we could even see the introduction of vaccines and medicine in some foods, like the potato that has been engineered in order to produce an edible vaccine against pathogenic E coli.

© Illustration by Jo Smolaga

Bacteria vs virus

Which is which, and why does it even matter?



The flu virus is covered in molecules that help it to get inside cells

When you've got a sore throat, the cause doesn't always seem important. Some microscopic nasty is waging war with your immune system, it hurts, and you just want to feel better. But whether it's bacteria or a virus on the rampage is actually very important.

Bacteria are some of the smallest living things on the planet, each made from just a single, primitive cell. Their insides are separated from the outside by a fatty membrane and a flexible coat of armour called the cell wall. Their genetic information is carried on loops of DNA, and these contain tiny factories called ribosomes, which use the genetic code to produce the molecules that the bacteria need to grow, divide and survive.

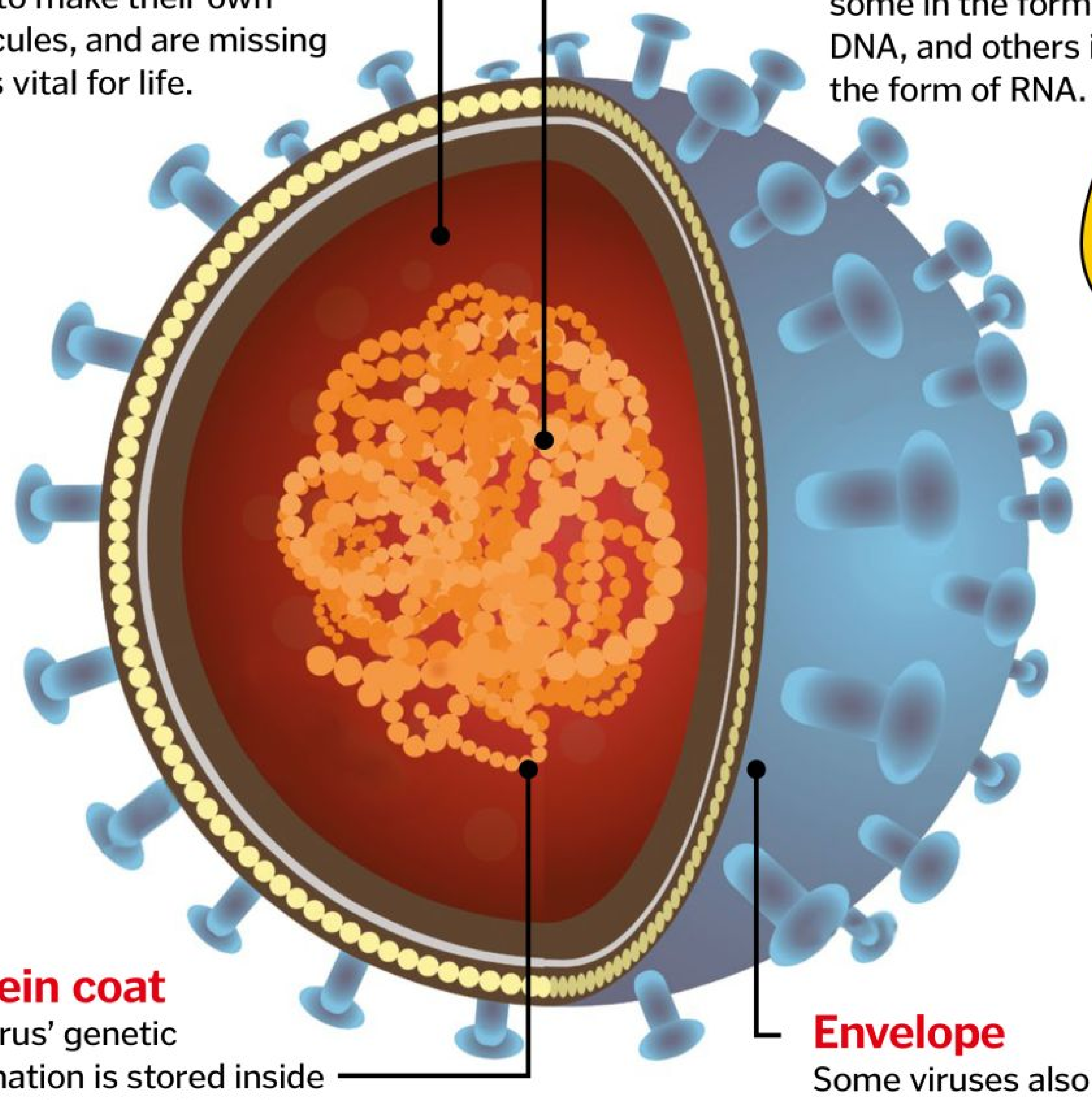
Viruses, on the other hand, are not technically alive. They carry genetic information containing the instructions to build more virus particles, but they don't have the equipment to make molecules themselves. To reproduce, they need to get inside a living cell and hijack its machinery, turning it into a virus factory.

Both bacteria and viruses can cause diseases, but knowing which is the culprit is critical to treating them effectively. Antibiotics can harm bacteria, but have no effect on viruses. Even your own immune system uses different tactics.

For bacteria, it unleashes antibodies – projectile weapons that stick invading microbes together, slowing them down and marking them for destruction. For viruses, your immune system can search for any infected cells before initiating a self-destruct sequence to dispose of anything lurking inside. But some viruses are able to endure our defences, and can remain inside us indefinitely.

Head to head

Both are microscopic, but take a closer look and the differences become clear

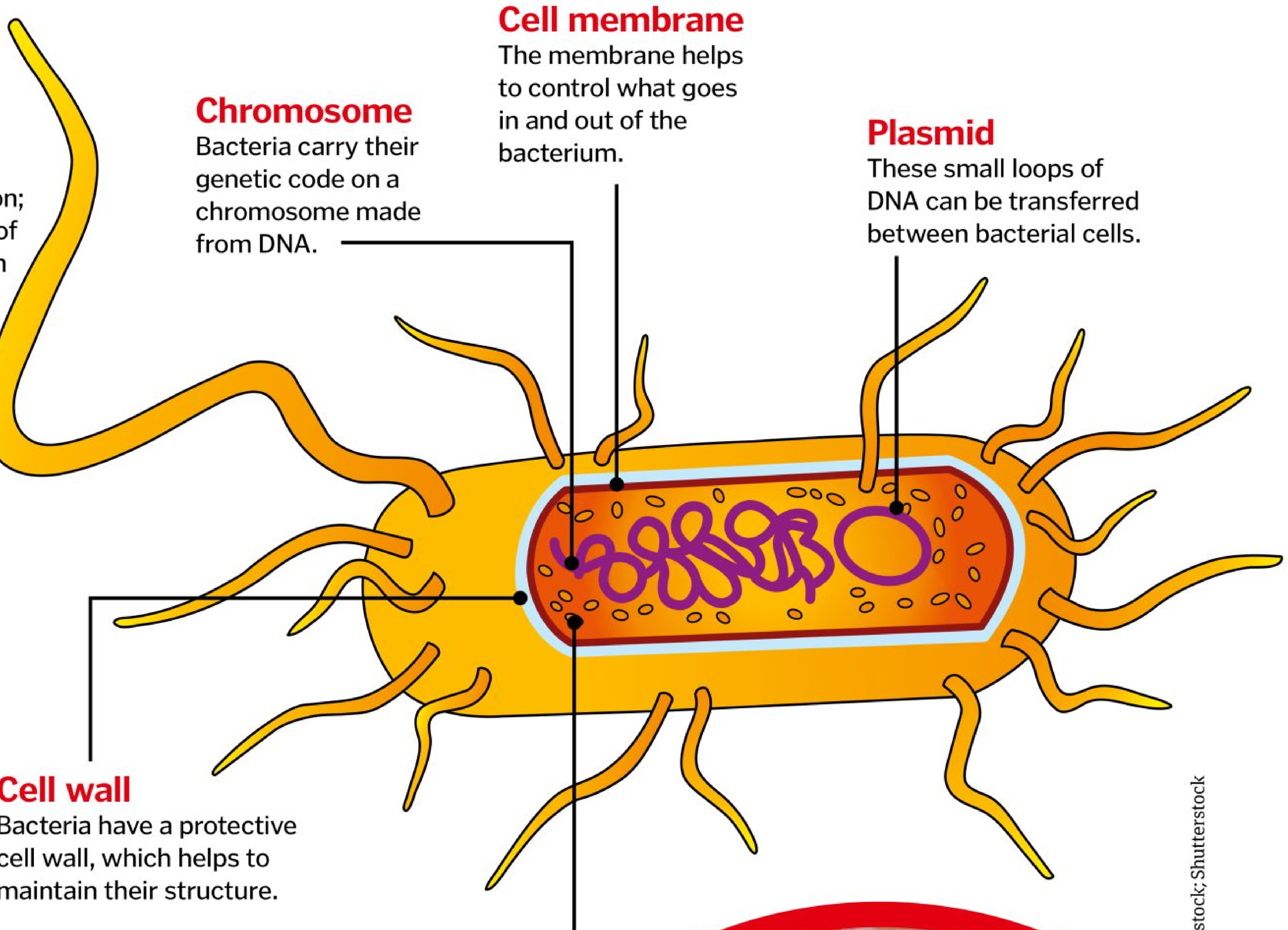


Not alive
Viruses do not possess the tools to make their own molecules, and are missing genes vital for life.

Nucleic acid
Viruses carry genetic information; some in the form of DNA, and others in the form of RNA.

Protein coat
The virus' genetic information is stored inside a protective covering of molecules called proteins.

Envelope
Some viruses also have an outer envelope, often made from fat and protein.



Chromosome
Bacteria carry their genetic code on a chromosome made from DNA.

Cell membrane
The membrane helps to control what goes in and out of the bacterium.

Plasmid
These small loops of DNA can be transferred between bacterial cells.

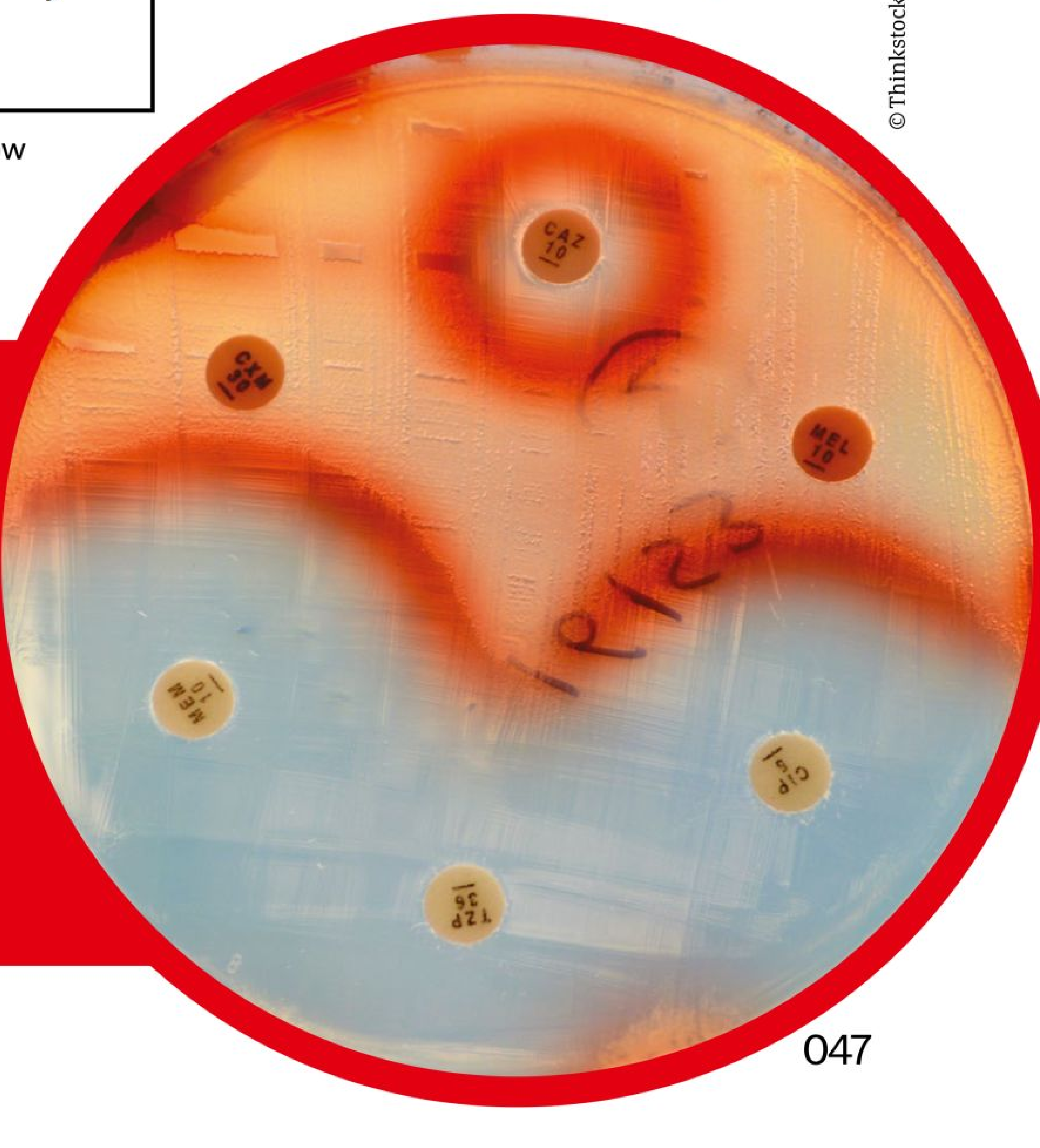
Cell wall
Bacteria have a protective cell wall, which helps to maintain their structure.

Ribosome
These structures allow bacteria to make the molecules that they need to live.

> "For viruses to reproduce, they need to get inside a living cell and hijack its machinery, turning it into a virus factory"

Antibiotic resistance

Antibiotics attack bacteria. They work by interrupting the way that the tiny cells divide, grow and repair. However, if an infection is caused by a virus, antibiotics won't help. Viruses don't work in the same way as bacteria, so antibiotics can't help to fend them off. It might not seem much of a problem, but every time antibiotics are used, it gives bacteria a chance to learn how to resist them. So every time a patient with a virus is given antibiotics, not only will they not get better, but bacteria lurking in their bodies will have a chance to see the drug and develop defences against it.



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Brain cells

Find out what's really going on inside your head

Your brain is an incredible thing. It is one of the most complex structures in the known universe, and for decades, scientists have been teasing it apart to find out what it's made of and how it works.

The brain is an electrical and chemical circuit, and nerve cells, or neurons, are the components. They each have a cell body, which contains their genetic code, an axon to transmit electrical impulses, and dendrites to receive them.

They are connected together at junctions known as synapses. When an impulse arrives, packets of molecules are released, passing the message on. Each neuron makes hundreds, or even thousands, of connections, producing the complicated patterns that drive human thought.

There are hundreds of different types of neuron in the brain, categorised according to their unique structure and function, and more are being discovered all the time. But they can't function on their own. They are supported by a network of glial cells – a name that literally means 'glue'.

There are three main types of glial cell. Oligodendrocytes have fatty branches, which they wrap around the conducting axons of nerve cells like the plastic coating on electrical wires. This provides insulation, preventing signals from getting crossed and speeding up their transmission along the chain.

Microglia are part of the immune system and act like an in-house cleanup crew, tracking down pathogens and clearing debris from the brain. Then there's the star-shaped astrocytes, which reach between nerve cells and blood vessels with their long, thin arms, shuttling nutrients, mopping up waste products, and even getting involved with chemical signalling.

How many cells?

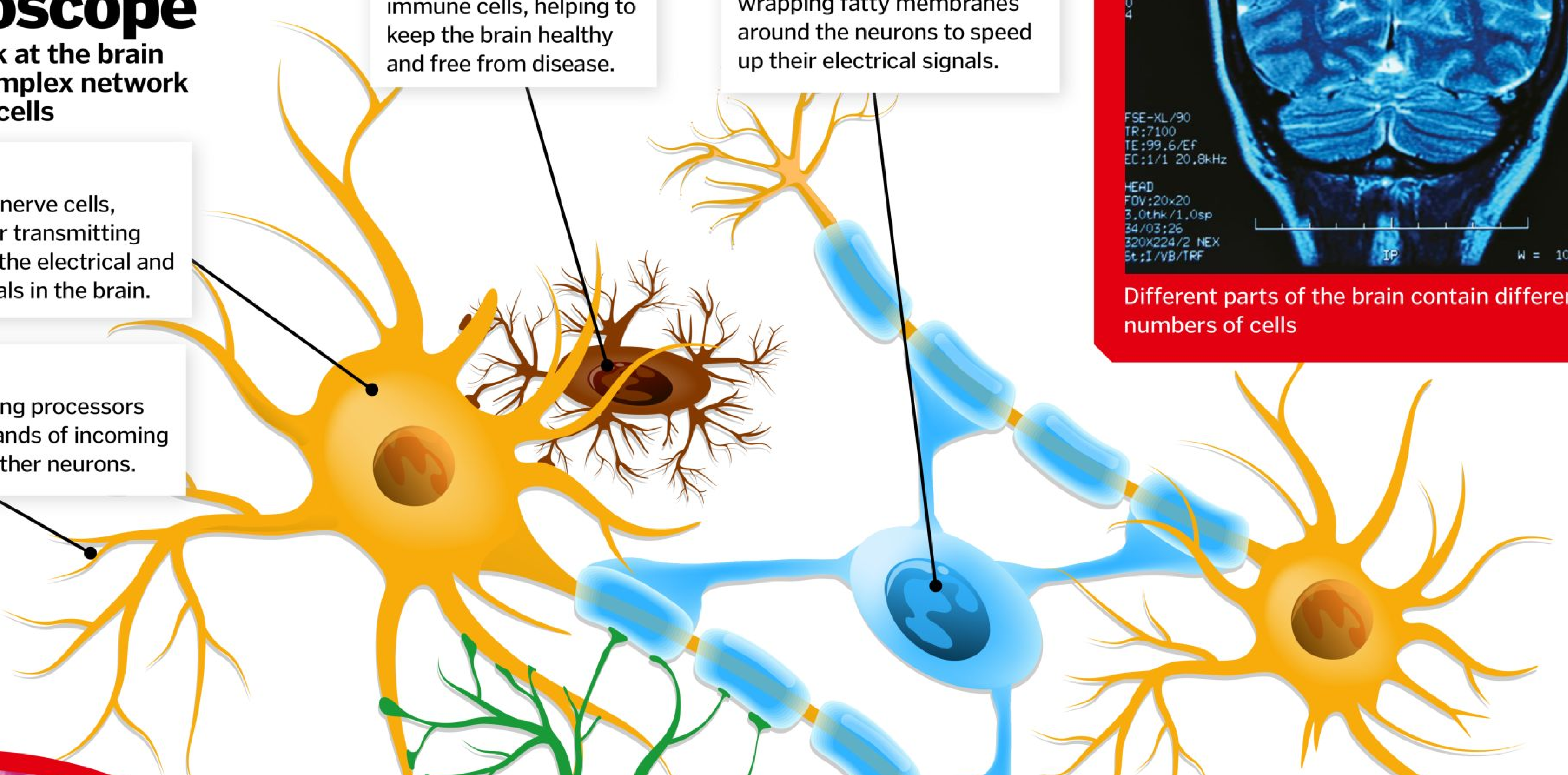
It's hard to know exactly how many cells are in the brain. Individual neurons have long, thin axons and branching trees of dendrites that cross over with their neighbours, forming a tangled mass that is almost impossible to accurately examine. One of the most commonly quoted estimates is 100 billion neurons, with anywhere between three and ten times as many supporting glial cells, but the latest research suggests that these numbers are in fact wrong.

Using a new technique for counting cells, scientists have come up with a different number. Each cell has one nucleus, and they can be stained up to make it easy to tell whether they belong to a neuron or a glial cell. Rather than count them under a microscope, the researchers popped the cells open and turned them into a 'soup' so that they could be quickly counted by machine. Using this technique, they revealed that there are closer to 86 billion neurons and about the same number of glial cells – far fewer than expected.

Different parts of the brain contain different numbers of cells

Under the microscope

A closer look at the brain reveals a complex network of different cells



Neuron
These are the nerve cells, responsible for transmitting and receiving the electrical and chemical signals in the brain.

Dendrite
These branching processors receive thousands of incoming signals from other neurons.

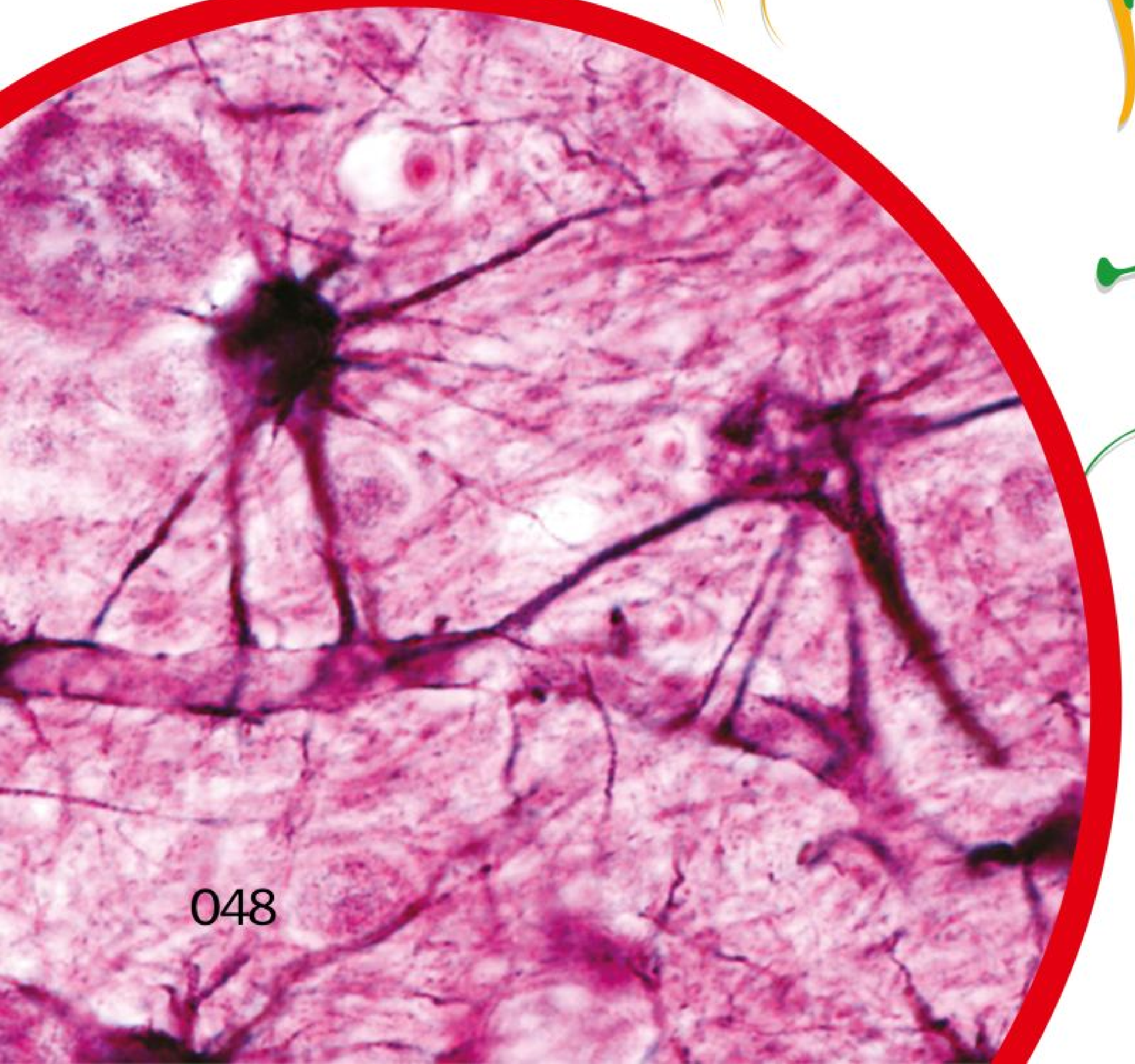
Microglia
These are specialist immune cells, helping to keep the brain healthy and free from disease.

Oligodendrocyte
These cells provide insulation, wrapping fatty membranes around the neurons to speed up their electrical signals.

Astrocyte
These star-shaped cells support the neurons, providing nutrients, clearing waste and contributing to signalling.

Axon
This part of the neuron transmits electrical signals towards neighbouring cells.

Synapse
Chemical signals are exchanged at these junctions, passing messages from one neuron to the next.



This microscope image shows astrocytes grabbing on to blood vessels with their 'feet'

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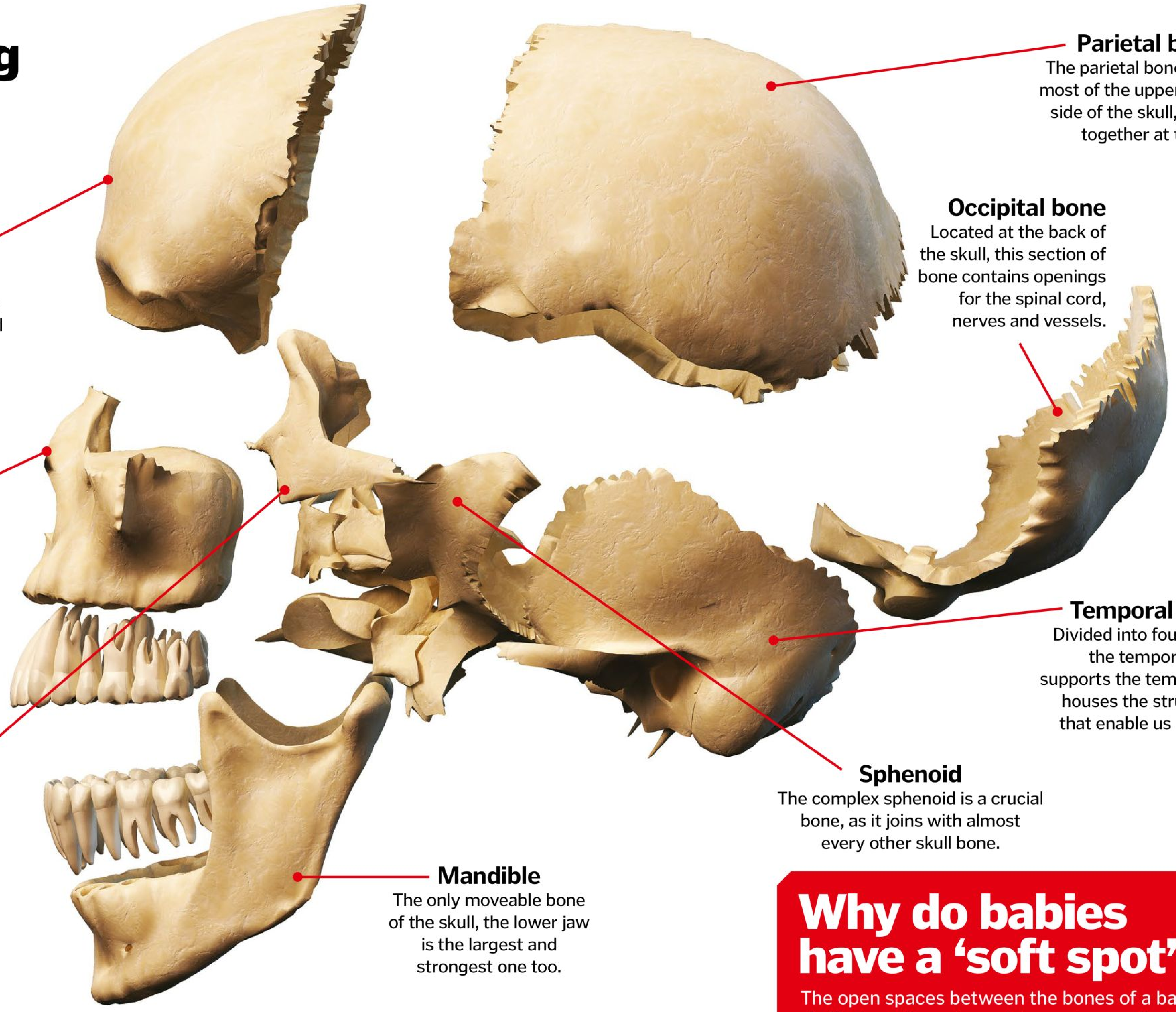
Breaking it down

How the various bones fit together to form the skull



Frontal bone
The single bone that forms the forehead, it is often considered a facial bone despite being a calvarial bone.

Parietal bones
The parietal bones form most of the upper lateral side of the skull, joining together at the top.

Occipital bone
Located at the back of the skull, this section of bone contains openings for the spinal cord, nerves and vessels.

Maxilla
Comprising part of the upper jaw and hard palate, the maxilla also forms part of the nose and eye socket.

Temporal bone
Divided into four parts, the temporal bone supports the temple and houses the structures that enable us to hear.

Sphenoid
The complex sphenoid is a crucial bone, as it joins with almost every other skull bone.

Zygoma
This bony arch spans from the cheek to just above the ear canal.

Mandible
The only moveable bone of the skull, the lower jaw is the largest and strongest one too.

The human skull

Understand the complex structure that supports our brain and facial tissues

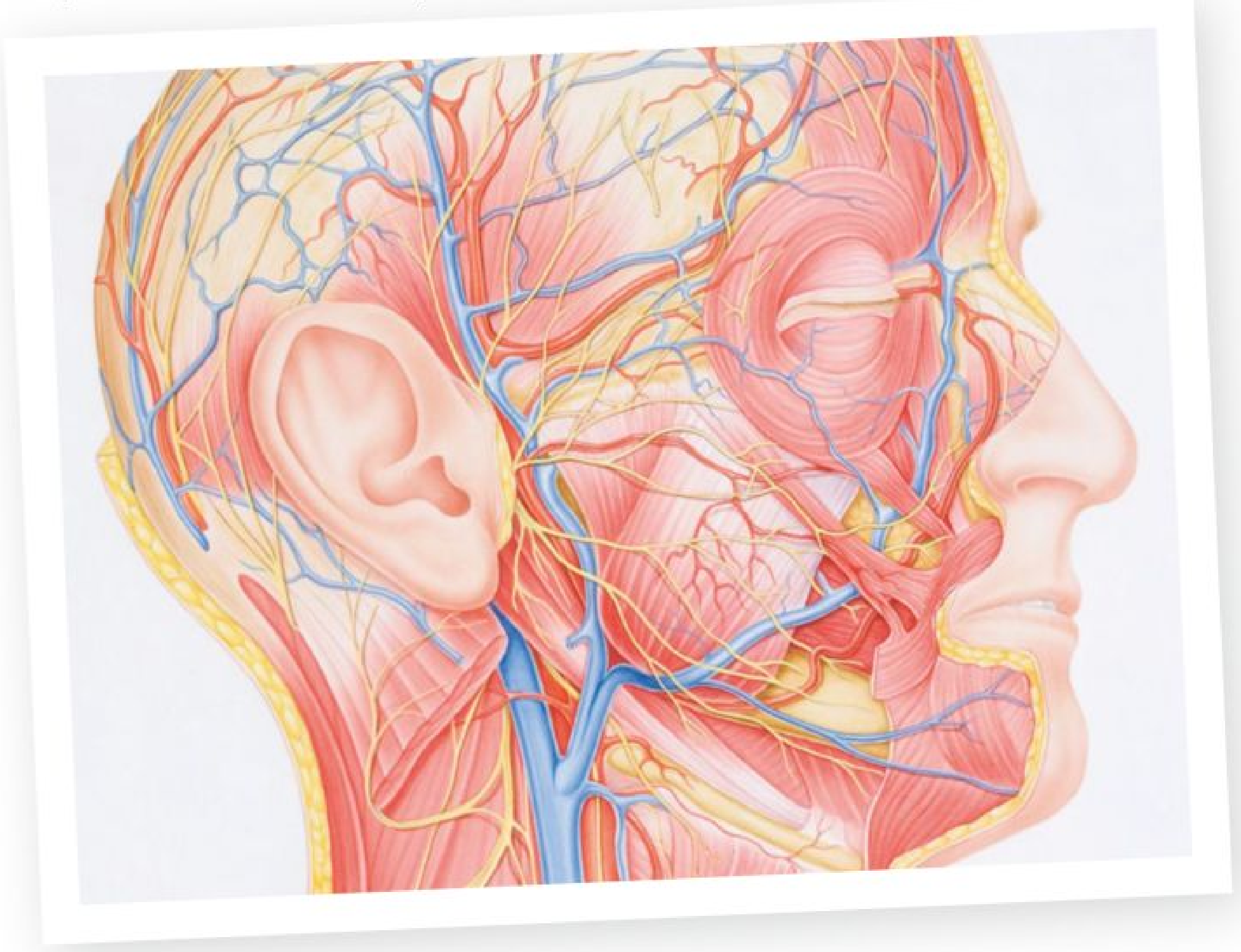
The human skull is made up of 22 bones that fall into two primary groups: the cranium, which consists of eight 'cranial' bones, and the facial skeleton, which consists of 14 facial bones. These bones are joined together by fibrous joints known as sutures. Unique to the skull, once these joints have fused together by the age of around 30 to 40, they are immovable.

The cranium consists of a roof part – known as the calvarium – and a complex base part. The calvarium helps to cover the cranial cavity, which the brain occupies, along with flat bones at the top and sides. The base of the brain case is divided into large spaces, and has various openings for the passages of cranial nerves, blood vessels and the spinal cord.

The facial skeleton provides support for the soft facial tissues, and its bones fuse together to house the orbits of the eyes, nasal and oral cavities, in addition to the sinuses. Only one of the skull's 22 bones is moveable, and that is the lower jaw.

As you can see in the diagram above, the skull is a complex structure, but then its main roles are to protect the brain and support the face, so this comes as no surprise.

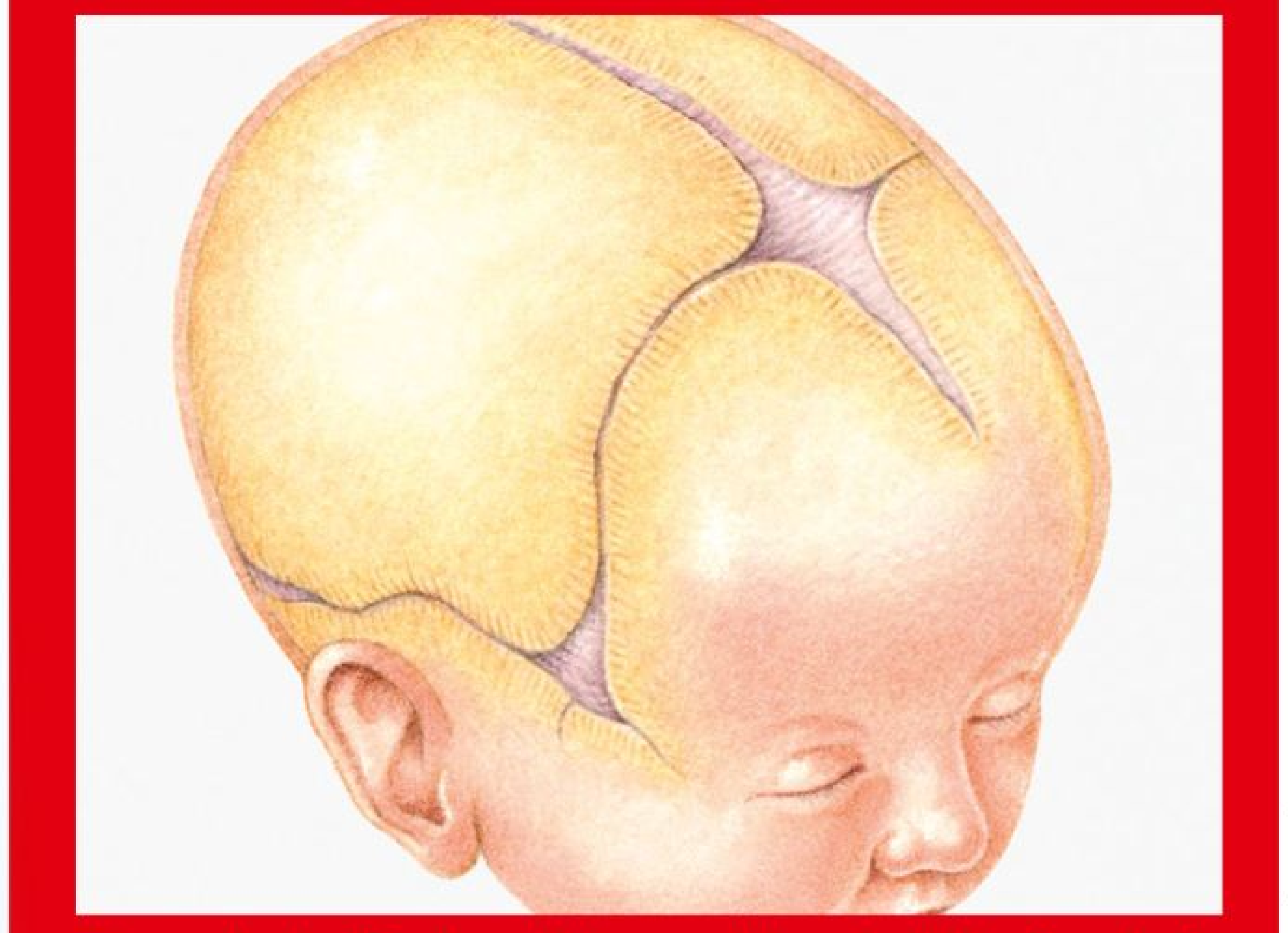
The skull does an impressive job of protecting superficial muscles, nerves and blood vessels



Why do babies have a 'soft spot'?

The open spaces between the bones of a baby's skull where the sutures intersect are called fontanelles. Covered in a protective membrane, there are two kinds of fontanelles: the anterior fontanelle – also known as the 'soft spot' – and the posterior fontanelle. The anterior fontanelle is where the two frontal and two parietal bones meet, and this area stays soft until the age of around two. The posterior fontanelle is where the two parietal bones and the occipital bone meet, and this area usually closes when a baby is a few months old.

The formation occurs as a means of helping the baby's head fit through the birth canal. The reason they remain open for some time is to enable the brain to develop and grow. It's important that the fontanelles don't close up too early – a process known as craniosynostosis – as this can result in various medical problems.



The anterior fontanelle is positioned at the front of the skull

© Getty; Thinkstock

YOUR SECRET SUPERPOWERS

Quirks of genetics have made some people everyday superheroes

Inside almost every cell in your body are 3 billion letters of genetic code. Hidden among them are around 20,000 genes, which carry the instructions to make proteins. Some form structural scaffolding, like the collagen in our skin. Others are enzymes that drive the chemistry of the body. Some are messengers that transmit signals. And others are involved in the transport or storage of substances in and out of cells and tissues.

When cells divide to make sperm and eggs, all 3 billion letters need to be copied in order to be passed on to the next generation, so mistakes are inevitable. Changes to the genes result in changes to their proteins, and different mutations have dramatically different effects. Imagine this sentence is a gene: "The quick brown fox jumped over the lazy dog." If you change the 'z' to an 's' (known as a point mutation in genetic terms), you'd still be able to guess the meaning. But if you changed 'f' to 'b', so 'fox' becomes 'box', the message completely changes. This is a 'missense' mutation.

Sometimes, a full stop is accidentally inserted part way through, ie "The quick brown." This is known as a 'nonsense' mutation, and it cuts the protein short. On other occasions, letters are inserted, or deleted, mid-gene. This shifts all of the letters along, changing the way the code is read: "The qui**yx** ckbro wnf oxjump edov ert hela zydog." This is known as a frameshift. Parts of genes, or entire genes, can also be duplicated, completely deleted, or crossed together.

Not all of the errors are good, but these mutations are the driving force behind evolution. Many are corrected automatically by the body, some end up being a slight disadvantage, and others can cause very serious genetic faults. But a few can prove to be beneficial, and a rarer few can lead to unexpected superpowers.

> "As with all complex genetics, the ACTN3 gene isn't the only factor"

SUPER SPRINTERS

Sporting talent isn't just down to practice and clean living – some of it is written in our genes

The construction and function of muscles depends on dozens of different genes, but there's one that's caught the eye of sports scientists. It's called ACTN3, and it carries the instructions for a protein called alpha-actinin-3; a molecule involved in high-force contraction of type 2 muscle fibres.

Type 2 fibres, also known as fast-twitch fibres, are used for rapid bursts of movement. They are powerful but they tire easily, and they are critical for sports like sprinting. Type 1, or slow-twitch fibres, in contrast, are better at sustained contraction and endurance. They're not as strong, but they last much longer.

Our muscles naturally have a mix of both, weighted according to what the muscle is mainly used for, but there's variation between individuals in the number and effectiveness of the different fibre types. Around one-fifth of people of European or Asian descent have a nonsense mutation part way through their ACTN3 gene, cutting the protein short. The result is a deficiency in alpha-actinin-3. This seems to affect how well force is transmitted through muscles, and how type 2 muscle fibres develop in response to training.

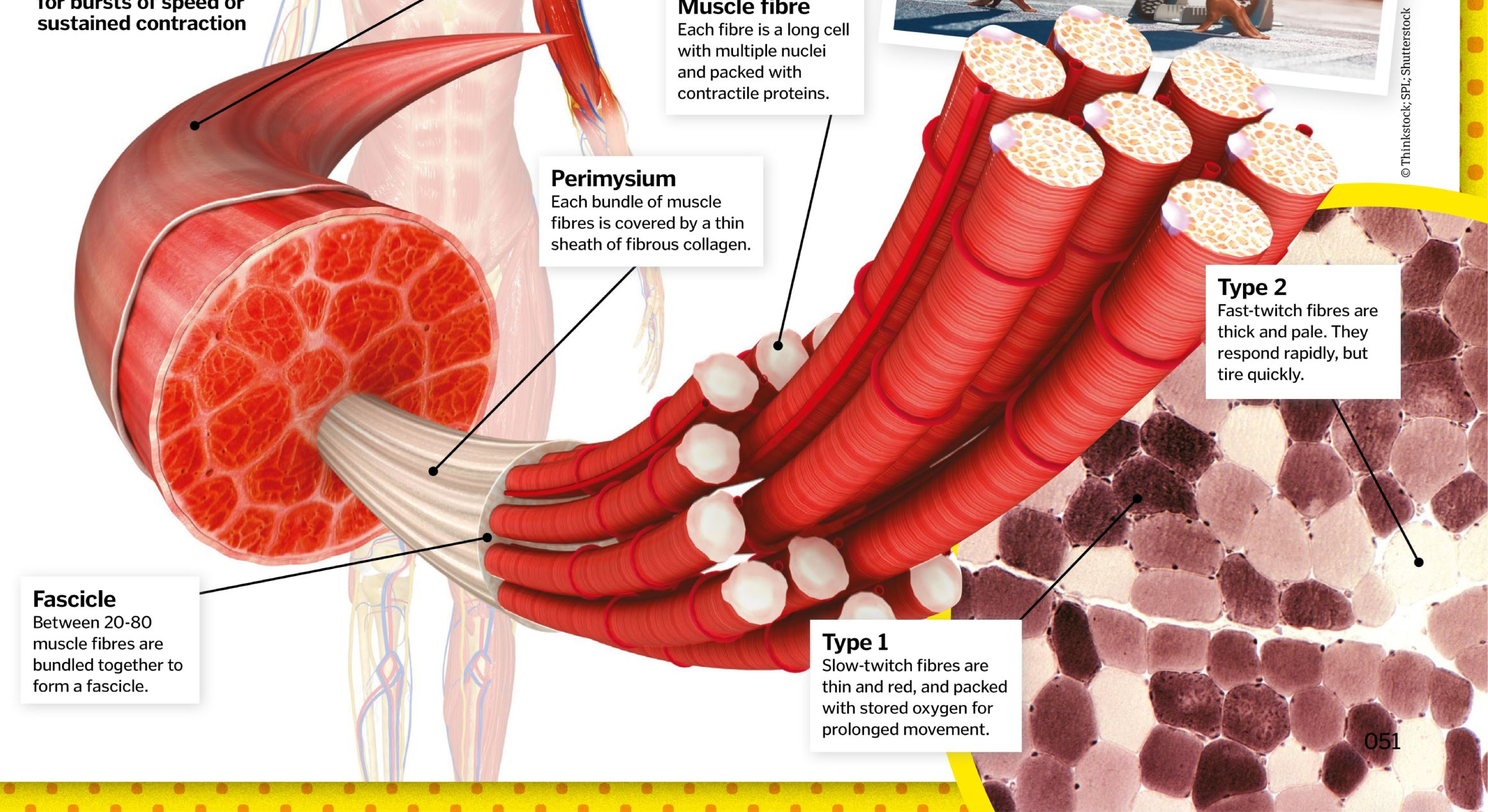
As a result, these people don't tend to be able to compete at the highest levels of sprinting. If you look at elite athletes, the proportion of people with the deficiency drops dramatically.

As with all complex genetics, this gene isn't the only factor. Elite male sprinters are more likely to have the deficiency than females, suggesting testosterone might override the disadvantage.

Elite sprinters are significantly less likely to have ACTN3 deficiency

Muscle fibres explained

Muscles contain fast- and slow-twitch fibres for bursts of speed or sustained contraction



Epimysium
The entire muscle is coated in a tough sheath of collagen, which connects to bone via a tendon.

Muscle fibre
Each fibre is a long cell with multiple nuclei and packed with contractile proteins.

Perimysium
Each bundle of muscle fibres is covered by a thin sheath of fibrous collagen.

Fascicle
Between 20-80 muscle fibres are bundled together to form a fascicle.

Type 2
Fast-twitch fibres are thick and pale. They respond rapidly, but tire quickly.

Type 1
Slow-twitch fibres are thin and red, and packed with stored oxygen for prolonged movement.

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SUPER SENSES

A quarter of the population can taste something that other people can't

The tongue is covered in bumps that are often, mistakenly, called taste buds. They are actually small mounds of tissue called papillae, and they come in four different varieties. One type can't taste at all, but the others all contain taste buds in their hundreds, or even thousands. These taste buds allow us to sense the five tastes: sweet, sour, salty, bitter and umami.

So called 'supertasters' are able to detect bitter molecules better than everyone else. There are also non-tasters, who are not able to detect certain bitter chemicals at all, and normal tasters, who are somewhere in between the two.

The variation is thought to be down to a couple of mutations in key tongue-related genes. The first is TAS2R38, which codes for a bitter taste receptor (a molecule that picks up bitter chemicals and starts the process of transmitting signals to the brain). The second is gustin, which codes for an enzyme found in the mouth. Thanks to their genes, supertasters end up with more receptors for certain bitter compounds, and a heightened sense of taste.

The best way to find out whether you're a supertaster is to taste a strip of paper coated in a chemical called n-Propylthiouracil, or PROP. To a supertaster, the strips taste intensely bitter, but to a non-taster, they taste of nothing at all. Another low-tech way to find out is to coat your tongue in food colouring and count your papillae – supertasters may have more than others.

> "Supertasters are able to detect bitter molecules better than everyone else"

Short sleepers

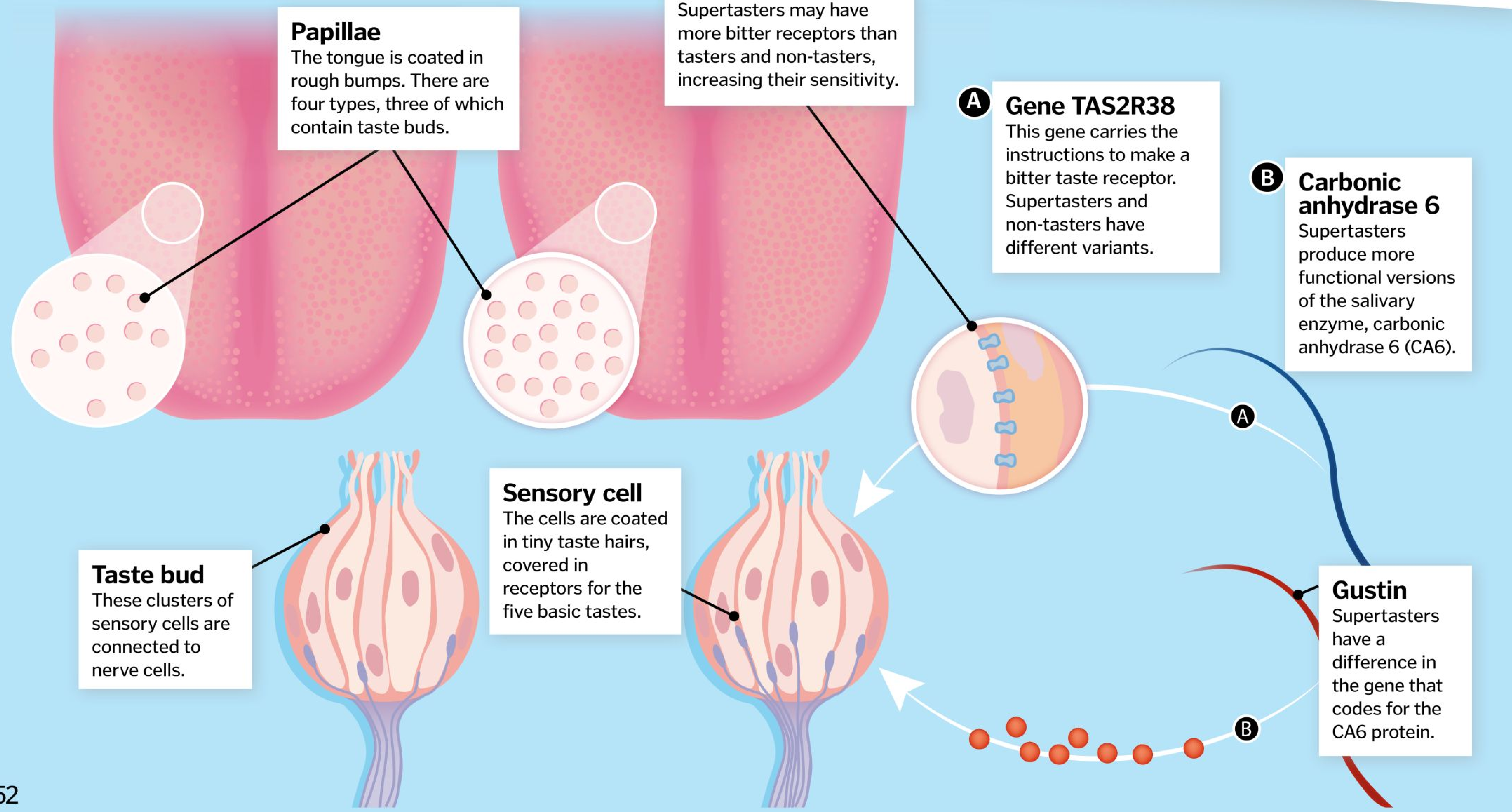
We need sleep to function, but some people need more than others, and that could be down to our genes. Sleep and wakefulness is controlled by an internal clock that sets and maintains a 24-hour cycle known as circadian rhythm (the name is derived from the Latin word *circa*, meaning 'around' and *diem*, meaning 'day'). A key controller of the cycle is a gene called DEC2.

People with a single letter change in their DEC2 gene have a remarkable ability. They average nearly two hours less sleep than the rest of the population without feeling overtired. It's a rare mutation, so scientists turned to mice to study it. They share many of our genes, and like us, need to sleep. When researchers simulated the same mutation in mice, they found that when their whole sleep cycle was shortened, they were still able to keep active for longer. This tiny change seems to add up to a big shift in sleep time.

Mice and humans share many similar genes, including those involved in sleep

Science of the super tongue

Supertasters owe their super sense to extra papillae with more taste receptors



Papillae
The tongue is coated in rough bumps. There are four types, three of which contain taste buds.

Bitter receptor
Supertasters may have more bitter receptors than tasters and non-tasters, increasing their sensitivity.

A Gene TAS2R38
This gene carries the instructions to make a bitter taste receptor. Supertasters and non-tasters have different variants.

B Carbonic anhydrase 6
Supertasters produce more functional versions of the salivary enzyme, carbonic anhydrase 6 (CA6).

Sensory cell
The cells are coated in tiny taste hairs, covered in receptors for the five basic tastes.

Taste bud
These clusters of sensory cells are connected to nerve cells.

Gustin
Supertasters have a difference in the gene that codes for the CA6 protein.

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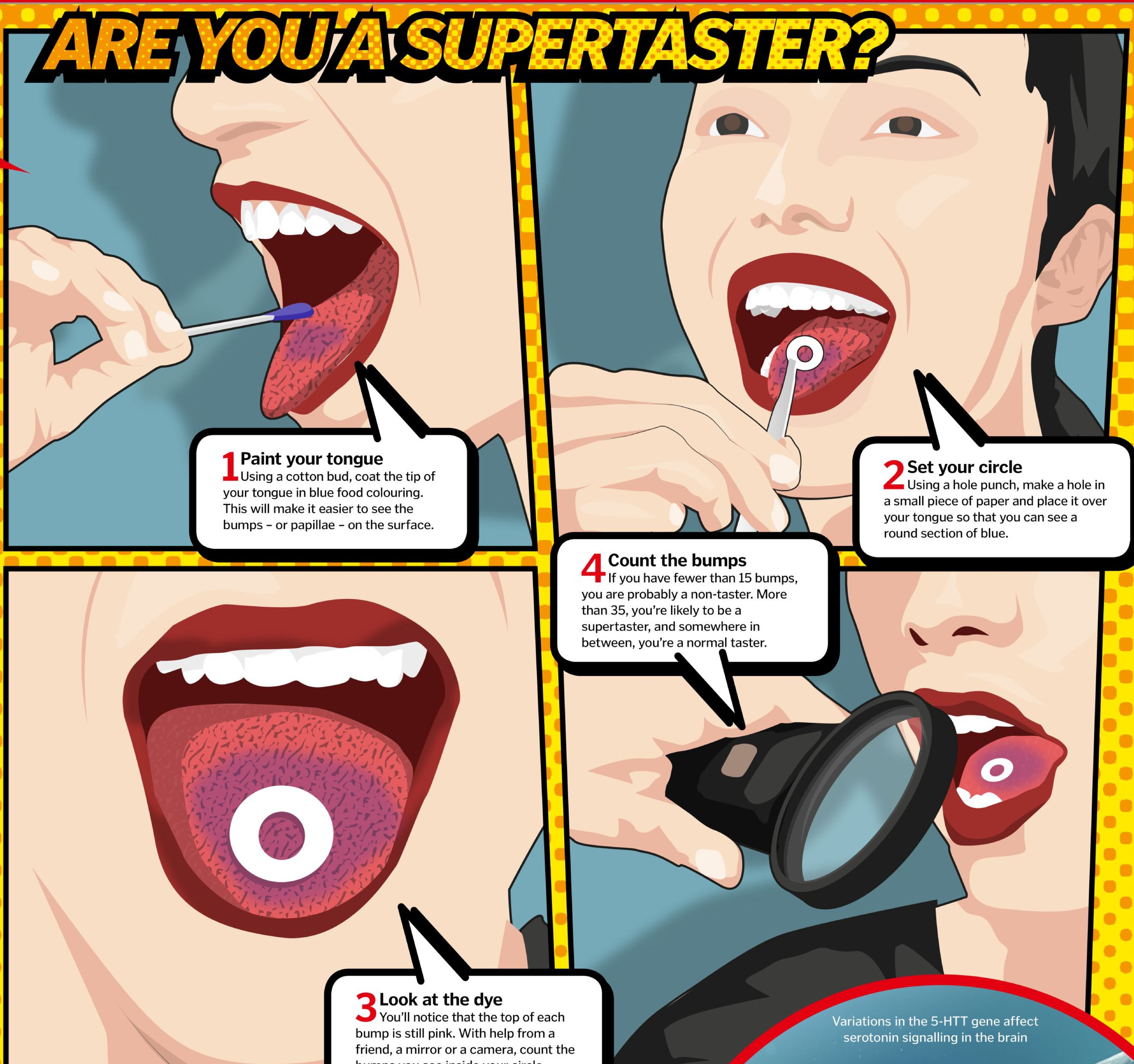
ARE YOU A SUPERTASTER?



1 Paint your tongue
Using a cotton bud, coat the tip of your tongue in blue food colouring. This will make it easier to see the bumps – or papillae – on the surface.

2 Set your circle
Using a hole punch, make a hole in a small piece of paper and place it over your tongue so that you can see a round section of blue.

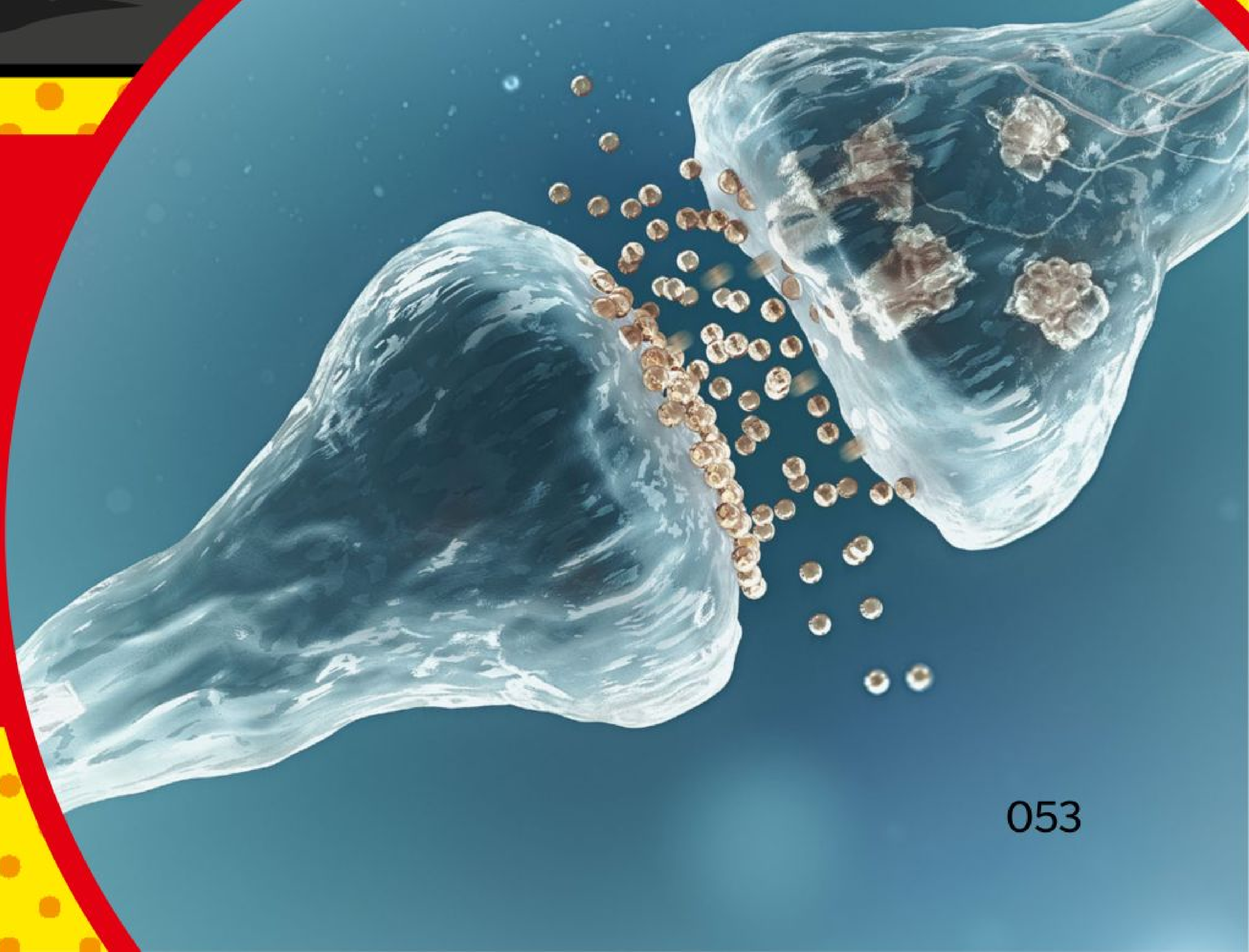
3 Look at the dye
You'll notice that the top of each bump is still pink. With help from a friend, a mirror or a camera, count the bumps you see inside your circle.

4 Count the bumps
If you have fewer than 15 bumps, you are probably a non-taster. More than 35, you're likely to be a supertaster, and somewhere in between, you're a normal taster.

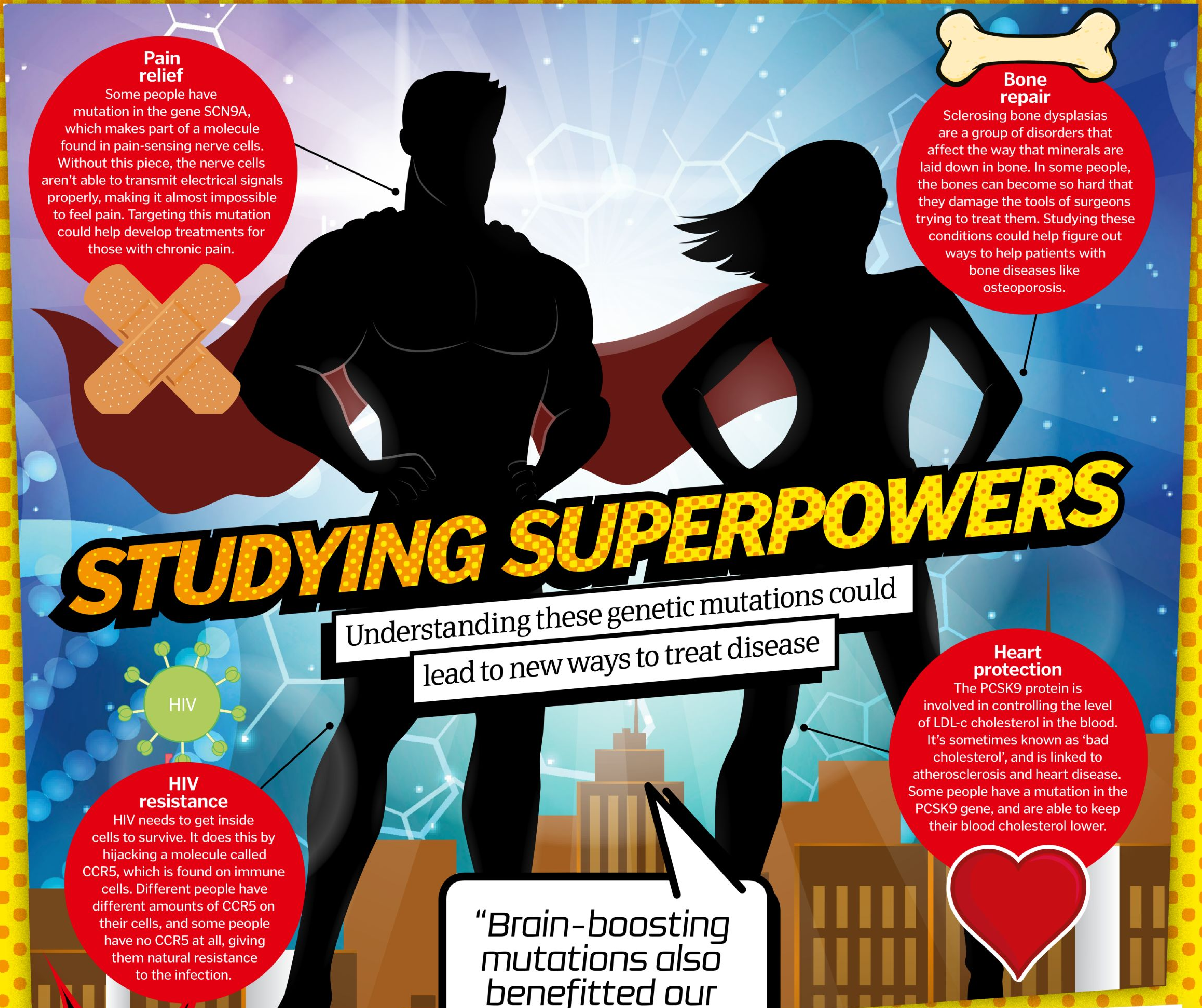
Depression resistance

Serotonin is sometimes known as the happiness hormone. It's a neurotransmitter produced in the brain and is used by nerve cells to communicate. We all have it, but small genetic changes seem to alter the way it affects us. 5-HTT is the serotonin transporter. Its job is to clear leftover serotonin out of the space between nerve cells after the signal has been sent. And 5-HTTLPR is a part of its gene.

It contains lots of repeated sections of genetic code, and people tend to have one of two variants: a short version with 14 repeats, or a long version with 16. People with the short version seem to have an increased likelihood of depression when they are exposed to major life stresses, while people with the longer version seem to be more resistant.



Variations in the 5-HTT gene affect serotonin signalling in the brain



STUDYING SUPERPOWERS

Understanding these genetic mutations could lead to new ways to treat disease

Pain relief

Some people have mutation in the gene SCN9A, which makes part of a molecule found in pain-sensing nerve cells. Without this piece, the nerve cells aren't able to transmit electrical signals properly, making it almost impossible to feel pain. Targeting this mutation could help develop treatments for those with chronic pain.

Bone repair

Sclerosing bone dysplasias are a group of disorders that affect the way that minerals are laid down in bone. In some people, the bones can become so hard that they damage the tools of surgeons trying to treat them. Studying these conditions could help figure out ways to help patients with bone diseases like osteoporosis.

HIV resistance

HIV needs to get inside cells to survive. It does this by hijacking a molecule called CCR5, which is found on immune cells. Different people have different amounts of CCR5 on their cells, and some people have no CCR5 at all, giving them natural resistance to the infection.

Heart protection

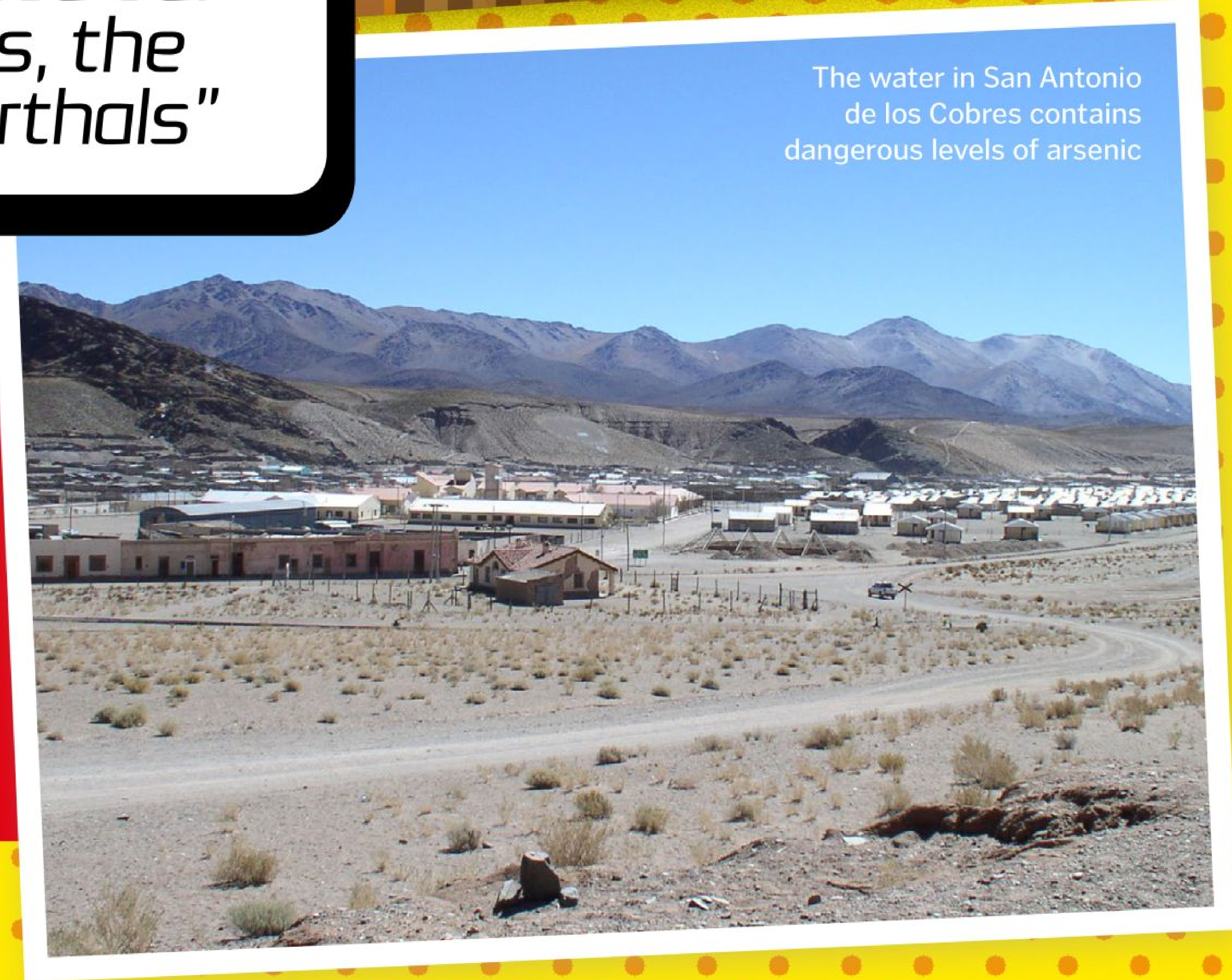
The PCSK9 protein is involved in controlling the level of LDL-c cholesterol in the blood. It's sometimes known as 'bad cholesterol', and is linked to atherosclerosis and heart disease. Some people have a mutation in the PCSK9 gene, and are able to keep their blood cholesterol lower.

> "Brain-boosting mutations also benefitted our cousins, the Neanderthals"

Poison resistance

Arsenic is a deadly poison. It can cause cancer, heart disease and lung problems. But the residents of San Antonio de los Cobres in Argentina have a secret weapon. The water from their local hills is contaminated, sometimes containing up to 20 times more arsenic than the maximum level recommended by the World Health Organization. Fortunately, thanks to a genetic mutation, they are able to resist its effects.

When arsenic enters the body, it is first changed into a compound called monomethylarsonic acid (MMA) and then into a compound called dimethylarsinic acid (DMA). This is done by molecules called methyltransferases. MMA is the most toxic, and this is where the people in San Antonio de los Cobres have an advantage. They have alterations in the genes that code for arsenite methyltransferase (AS3MT), allowing them to quickly break it down into DMA, therefore shielding their bodies from the worst of the effects.


The water in San Antonio de los Cobres contains dangerous levels of arsenic

Small genetic changes set us apart from our closest living relatives

MADE OF MUTATIONS

We are who we are thanks to a series of genetic mutations

Our genes are 98.8 per cent the same as the genes of a chimpanzee. Although that difference might sound small, in a sequence of 3 billion letters, it equates to a lot of code.

We share a common ancestor with the other great apes. Around 10-15 million years ago, chimps, gorillas and humans didn't exist. In our place was our shared primate ancestor, who contained an important gene called RNF213.

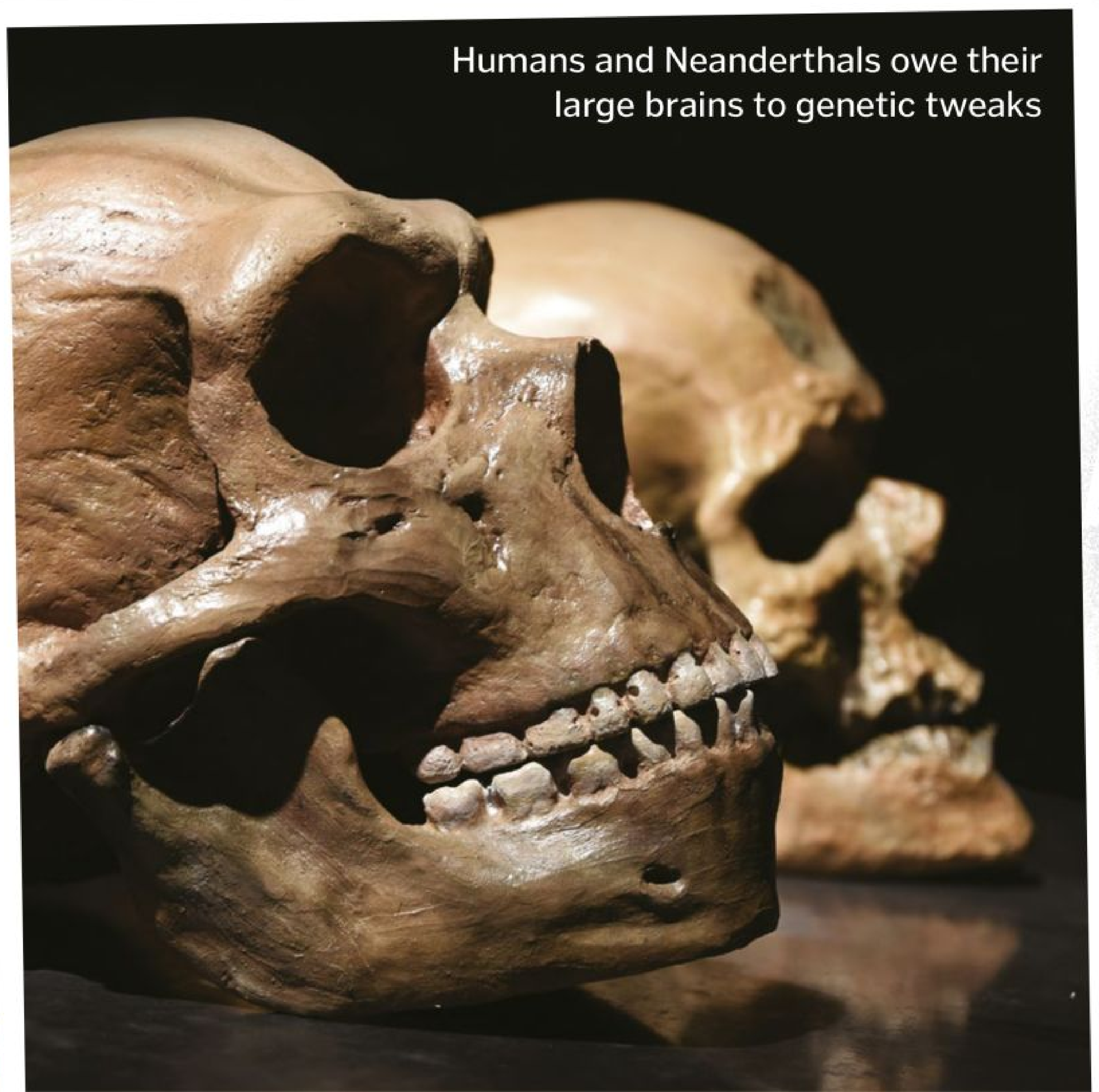
The function of this gene is not fully understood, but a mutation found in modern humans leads to a narrowing of the carotid artery. This major vessel supplies blood to the head, and changes in the gene when our ancient ancestor was alive are thought to have helped improve blood supply to the growing brains of great apes. But the other apes didn't develop human-like intelligence. More genes have contributed to the development of our cognitive abilities as time has gone by.

An area of the genome called Human accelerated region 1 (HAR1) evolved quickly after the ancestors of humans and chimpanzees parted ways between 5-7 million years ago. It's expressed in neocortex; the most recently evolved part of the brain. In chimps, the molecule made using the HAR1 code is a disorganised structure, but in humans it looks like a clover. This more orderly orientation alters the expression of other genes, changing the way that our brains develop.

Our ancestors also ended up with a duplication of a gene called SRGAP2, which allowed the nerve cells in the neocortex to make stronger connections. Changes later accumulated in a gene called FOXP2, which aids language learning by helping us to convert our declarative memory (memory of facts and events) into procedural or habitual memory (the long-term unconscious memory that allows us to perform tasks).

All three of these brain-boosting mutations also benefitted our close relatives, the Neanderthals. But after our ancestors diverged around 500,000-600,000 years ago, more genetic changes continued to give us homo sapiens the edge. One was an edit in a gene called AHR, which helped to shield us from the toxic effects of smoky fires, and another was the duplication of a gene called AMY1, which codes for amylase, an enzyme that helps to break down carbohydrates inside the food we eat.

Over time, these little genetic tweaks have allowed us to adapt to our changing environments, all adding up to make us the planet's dominant species.



Humans and Neanderthals owe their large brains to genetic tweaks

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Unexplained superpowers

RAPID REFLEXES

Japanese Iaido master, Isao Machii, can cut a speeding BB gun pellet in half using a samurai sword.

PHOTOGRAPHIC MEMORY

Stephen Wiltshire can memorise and redraw a cityscape after only a few minutes observing it.

SUPER SIGHT

Veronica Seider claimed to have been able to identify a person from over a mile (1.6 kilometres) away.

NUMERICAL MASTERY

Daniel Tammet is able to memorise enormous strings of numbers, once reciting pi to 22,514 decimal places.

SEEING DIFFERENTLY

Daniel Kish lost his eyesight as a child, but can 'see' with his ears using clicks for echolocation.

Your biological clock

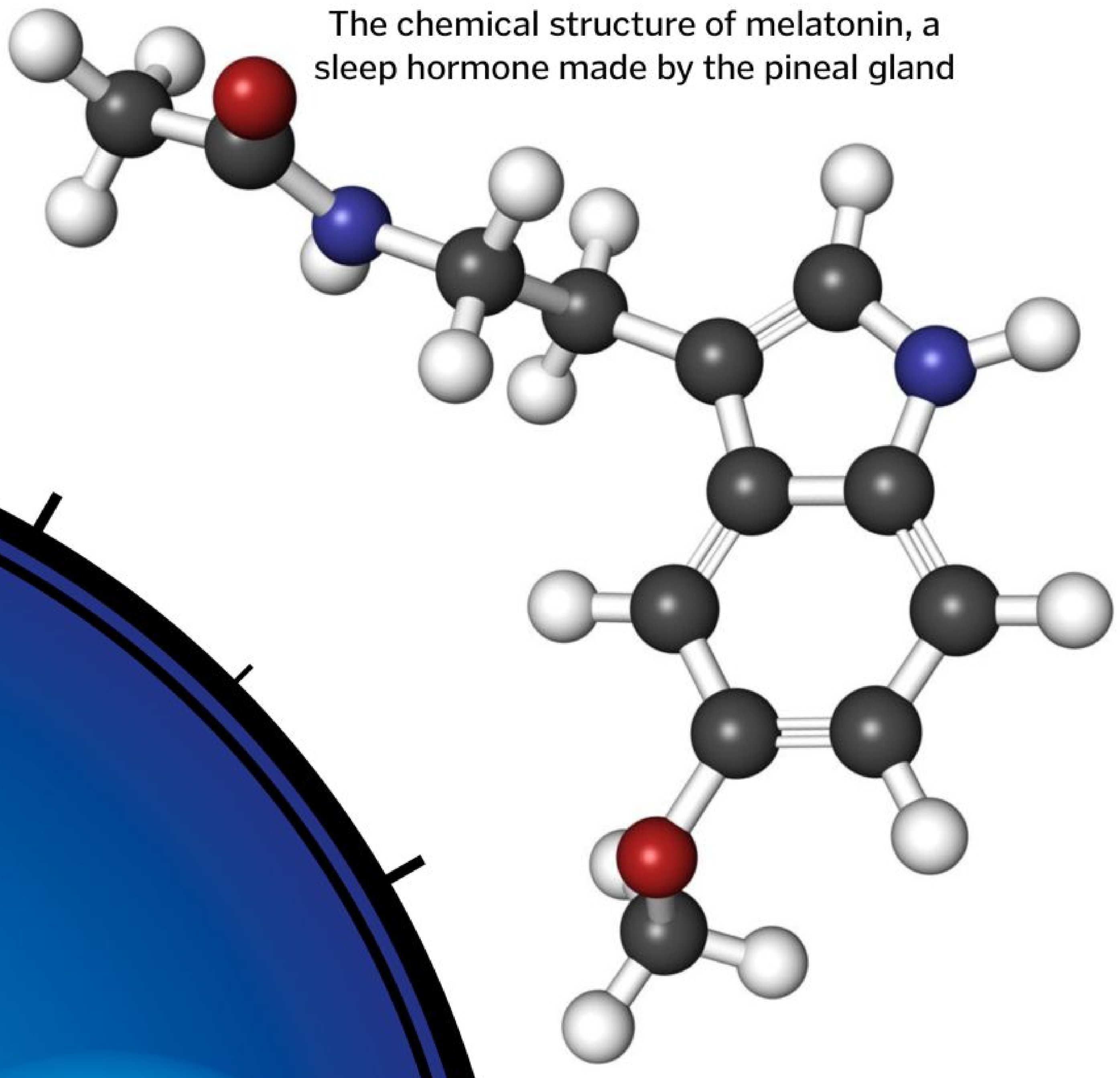
How biochemical processes keeps you in sync

Our bodies run on an in-built 24-hour clock embedded in a part of the brain called the suprachiasmatic nucleus (SCN). Its 20,000 nerve cells sit in the middle of the brain above the back of the eyes and on top of a structure called the hypothalamus. These are the body's master timekeepers, setting the rhythm for sleeping, waking, eating, and hormone release.

Even in a test tube, cells from the SCN keep time. They are stuffed with molecules called transcription factors, which change the production levels of other molecules on a 24-hour cycle. The master regulators are known as BMAL and CLOCK. Together, these two molecules activate the production of molecules called periods and cryptochromes. As levels of periods and cryptochromes rise, they feed back to BMAL and CLOCK, switching production off again. This causes the amount of these molecules to go up and down in cycles, forming the basis for a precise timekeeper.

Like any clock, the SCN can run fast or slow, so the time is reset, or entrained, every day by daylight. This is done by light-sensitive cells in the back of the eye known as intrinsically photosensitive retinal ganglion cells. They don't produce images when they detect light: instead they send signals to the SCN via a bundle of nerve tissue called the retinohypothalamic tract, syncing the master clock, which in turn messages the rest of the body about the time.

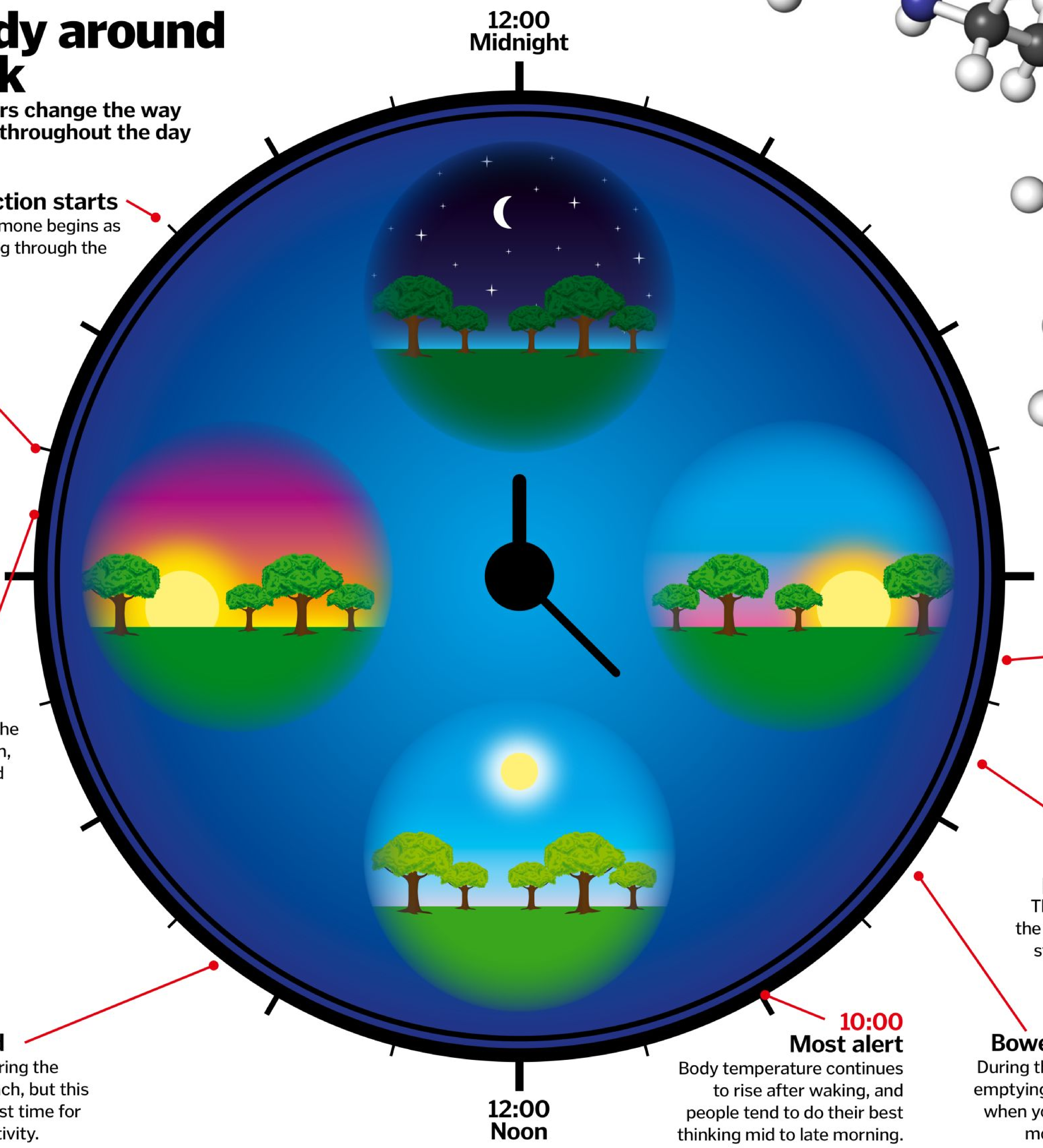
Blue light emitted by screens can confuse our body clocks at night



The chemical structure of melatonin, a sleep hormone made by the pineal gland

Your body around the clock

Internal timekeepers change the way our bodies behave throughout the day



21:00
Melatonin production starts
Release of the sleep hormone begins as darkness falls, continuing through the night until sunrise.

19:00
Highest temperature
Fluctuations in temperature set by the SCN help to keep the rest of the clock in sync. By the evening, body temperature is at its highest.

18:30
Highest blood pressure
Blood pressure follows the so-called 'dipper' pattern, rising during the day and dropping again at night.

14:30
Most coordinated
Sleepiness can set in during the early afternoon after lunch, but this is also reportedly the best time for coordinated physical activity.

6:45
Blood pressure up
Morning light enters the eye, sending a signal to the SCN to reset the circadian clock. Temperature and blood pressure soon rise.

7:30
Melatonin production stops
The SCN sends signals to the pineal gland telling it to stop producing the sleep hormone, melatonin.

8:30
Bowel movement
During the night, stomach emptying slows down, but when you wake up bowel movement restarts.

10:00
Most alert
Body temperature continues to rise after waking, and people tend to do their best thinking mid to late morning.

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How hands work

Our hands are complex feats of biological engineering

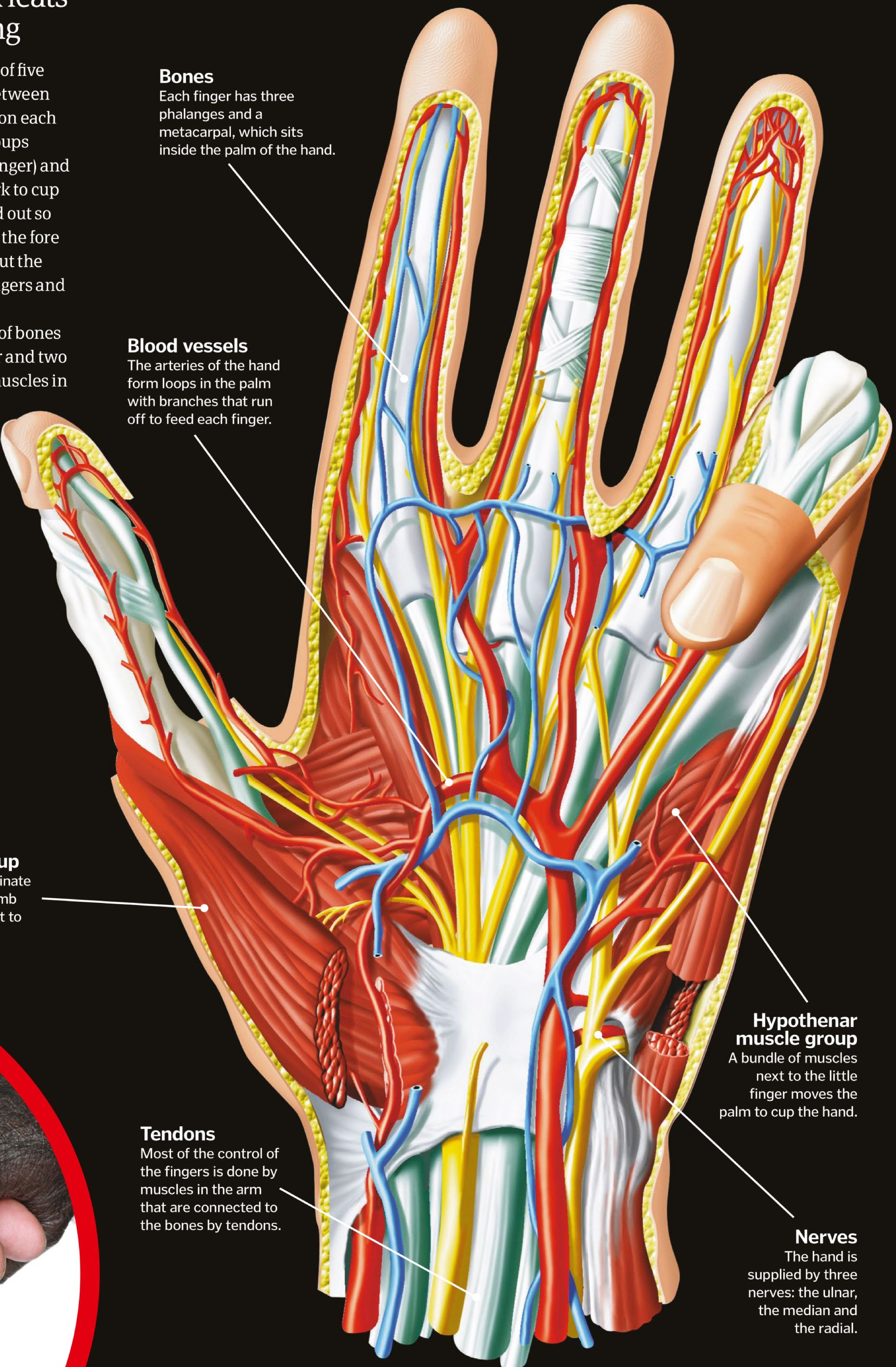
The palm of the hand is made up of five bones called metacarpals. In between are the interossei muscles, and on each side of the palm are bulging muscle groups called the hypothenar (near the little finger) and the thenar (near the thumb). These work to cup the hand and to move the thumb in and out so that it can grip. The bones belonging to the fore and middle fingers don't move much, but the ones connected to the little and ring fingers and the thumb are much more mobile.

The fingers themselves are made up of bones called phalanges – three for each finger and two for the thumb. They are connected to muscles in the forearm by tendons that run through the wrist. The flexor tendons run up on the underside through a space called the carpal tunnel – they bend the fingers. The extensor tendons come across the top of the wrist – they pull the fingers straight.

All of this movement is controlled by three nerves: the median, radial and ulnar. The median nerve supplies the thumb, the index and middle fingers, half of the ring finger and the palm of the hand. The ulnar feeds the other half of the ring finger and the little finger, and the radial looks after the thumb and the back of the hand.

Hand anatomy

Discover the bones, muscles, tendons and nerves inside the human hand



Bones
Each finger has three phalanges and a metacarpal, which sits inside the palm of the hand.

Blood vessels
The arteries of the hand form loops in the palm with branches that run off to feed each finger.

Thenar muscle group
A bundle of muscles coordinate the movements of the thumb across the palm, enabling it to touch the fingers.

Hypothenar muscle group
A bundle of muscles next to the little finger moves the palm to cup the hand.

Tendons
Most of the control of the fingers is done by muscles in the arm that are connected to the bones by tendons.

Nerves
The hand is supplied by three nerves: the ulnar, the median and the radial.

Only a few other animals have opposable thumbs like ours

Science of STRESS

WHAT HAPPENS TO YOUR BODY WHEN IT'S PUT UNDER PRESSURE?

The man who first defined stress, Hans Selye, once told reporters: "everyone knows what stress is, but nobody really knows." From a mental health perspective, stress describes the feeling of excessive emotional pressure. It can manifest itself as anxiety, trouble sleeping, altered eating patterns, destructive behaviour, headaches or muscle pain. This is the stress that we are all familiar with. But, from a broader biological perspective, stress is the body's response to any kind of disruption, whether it's psychological trauma, extreme temperature, lack of food, or confrontation with a predator.

There's no proper medical definition of stress, but when it comes to biology, it describes any threat to the body's normal balance. In order to cope with that threat, whether it's real or imagined, the body takes steps to protect itself. The bloodstream floods with chemical signals that heighten awareness, increase heart rate, quicken breathing, dull pain, and even induce euphoria. At the same time, non-essential functions like digestion and growth slow right down. When the stress response is activated surviving becomes the key concern; the future becomes less important.

The brain kick-starts the stress response. The amygdala, which deals with emotion and fear, sends a message to the hypothalamus, setting off a chain of electrical and chemical messages that prepare the body to respond. The first step is to put the nervous system into 'fight or flight' mode. It does this by signalling to the adrenal glands to increase production of adrenaline.

This chemical messenger surges into the bloodstream, triggering a wave of energy release by raiding the body's stores of fats and glycogen. Blood sugar rises and fatty acids are released to fuel the body in its time of need. These molecules are then shuttled to the muscles and brain by the bloodstream. Blood vessels in non-essential areas constrict, heart rate increases and breathing becomes faster, diverting extra resources to the places that need them most. Senses become heightened and the brain is put on alert. This response happens instantly, sometimes even before the conscious brain has processed it.

Depending on the situation – and the individual – the exact pattern of these chemical surges differs. If escape or confrontation is not an option, another response, known as 'aversive vigilance' might replace 'fight or flight'. Under these circumstances, movement stops, and blood is diverted away from the skin and extremities to the organs in the core.

Rather than revving the body up for physical activity, this response helps to minimise bleeding in case of injury. Though most stresses we experience now don't carry a risk of physical harm, this would have been useful in our evolutionary past. Which response is chosen varies on circumstances, but individuals are more likely to favour one or the other, and it's thought that these patterns are set early in life.

At the same time, a slower but more persistent stress response is also activated. The hypothalamus pumps out a molecule called corticotropin-releasing factor (CRF). This is the

The stress response

The body has a well-tuned system for dealing with the first signs of stress

1. Hypothalamus
This part of the brain is responsible for maintaining balance in the body, and it kicks off the stress response.

2. Pituitary
This pea-sized organ produces many hormones, including the stress messenger adrenocorticotropic hormone.

3. Adrenals
These glands are found on top of the kidneys, and produce steroids in response to stress.

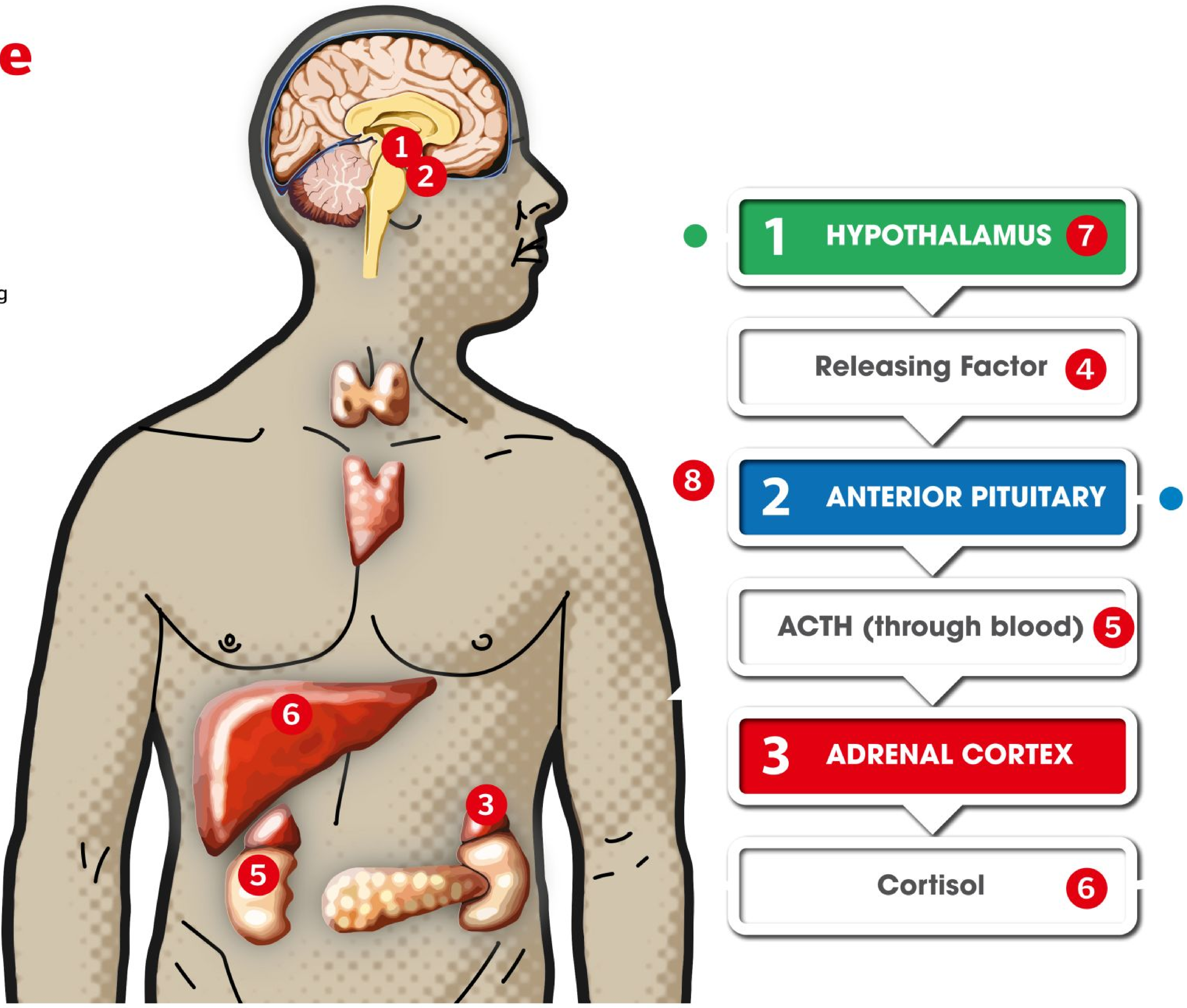
4. Corticotropin releasing factor
This chemical messenger carries the stress signal from the hypothalamus to the pituitary.

5. Adrenocorticotropic hormone
This hormone travels through the bloodstream, carrying the chemical message to the kidneys.

6. Cortisol
These natural steroids trigger changes across the body, helping it to deal with stress.

7. Activation
Several areas of the brain feed into the hypothalamus, triggering the stress response.

8. Suppression
High levels of glucocorticoids in the blood feed back to the brain, switching off the stress response.



Stress isn't just human

Bacteria
These microbes cope with changes to their environment by altering the way they use their genes. Molecules called sigma factors change which genes are switched on, and which are turned off.

Plants
Water stress can be a real problem for plants, so they respond by conserving moisture. This includes producing rapid chemical signals that close the pores in their leaves.

Fish
Fish have a similar stress response to other vertebrates, with a cycle of chemical signals that starts in the brain, preparing the body to release energy and shut down unnecessary activity.

Birds
Like us, birds make corticosteroids in response to stress. The amount goes up in birds that breed in higher places, which helps them to cope with the risks associated with nesting at high altitudes.

Mice
These rodents are often used as a model for human biology, but recent research showed that they are stressed by male scientists. The effect seems to be related to their smell, and it may skew the results of tests.

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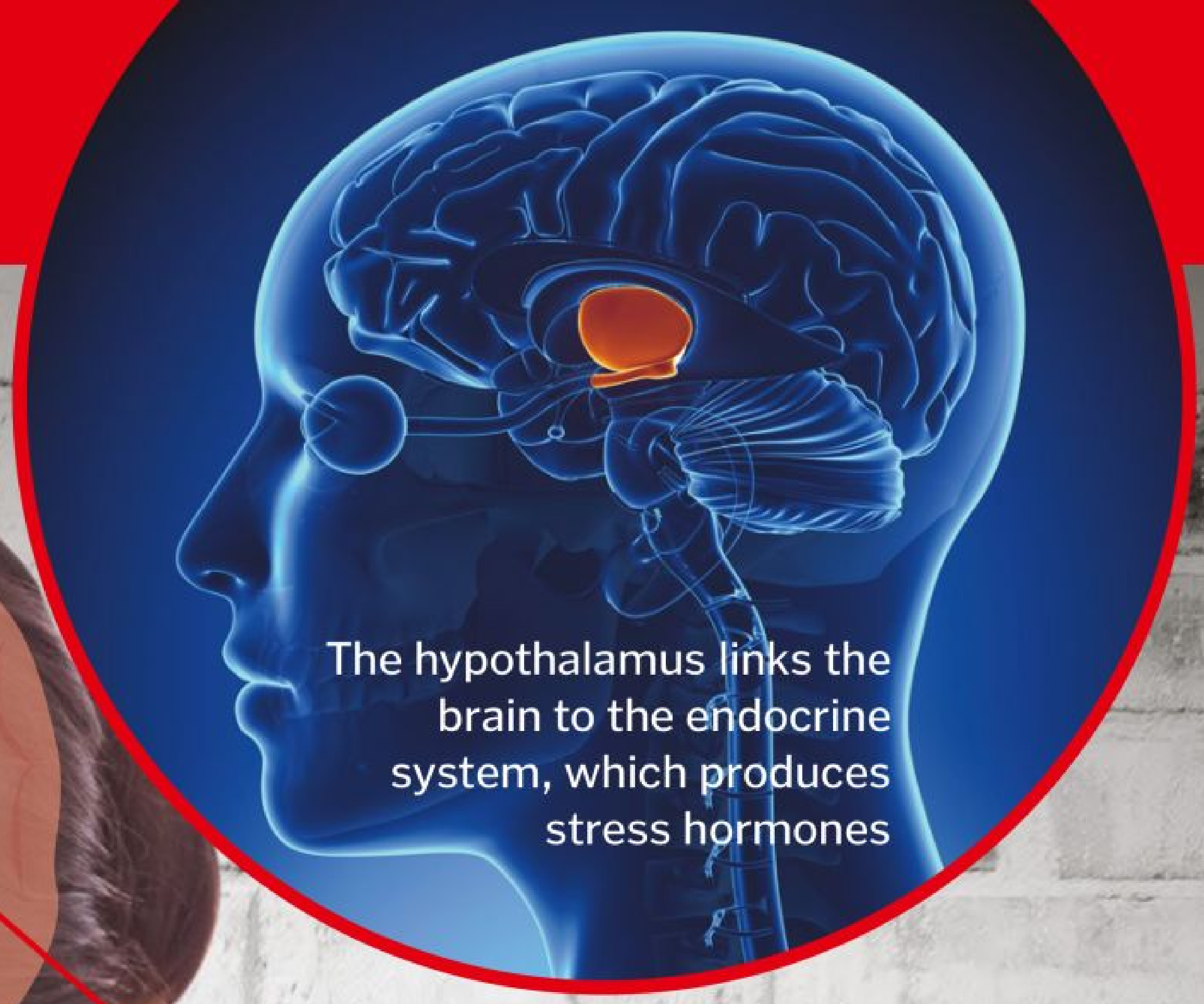
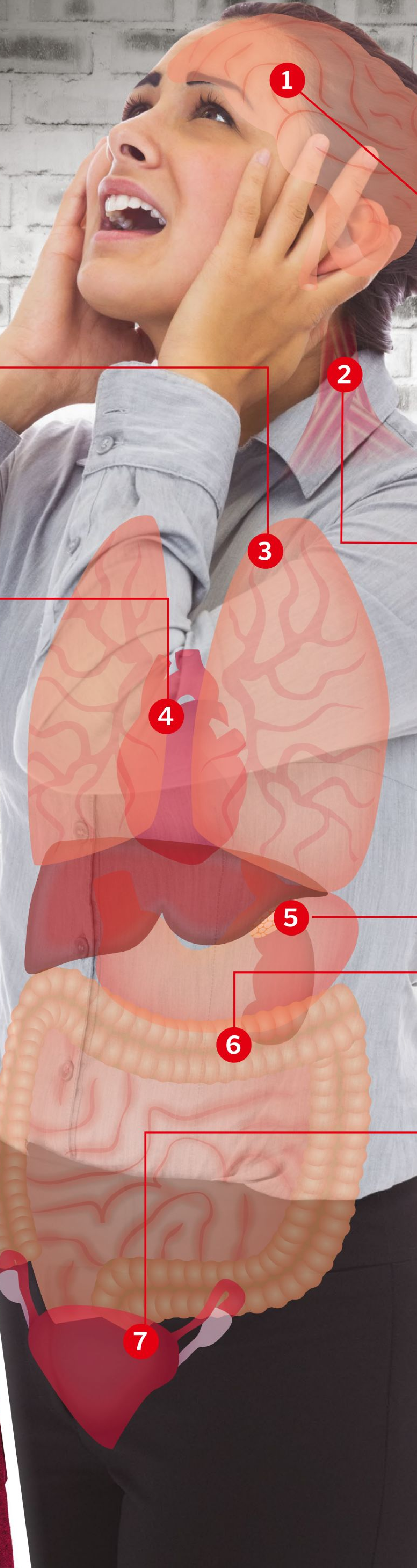
The effects of stress

Too much stress can have a negative effect on different parts of the body



The hypothalamus links the brain to the endocrine system, which produces stress hormones



Nerves
Stress during brain development can affect the structure of the growing brain.

Muscles
Tense muscles in the head, shoulders and neck can lead to headaches.

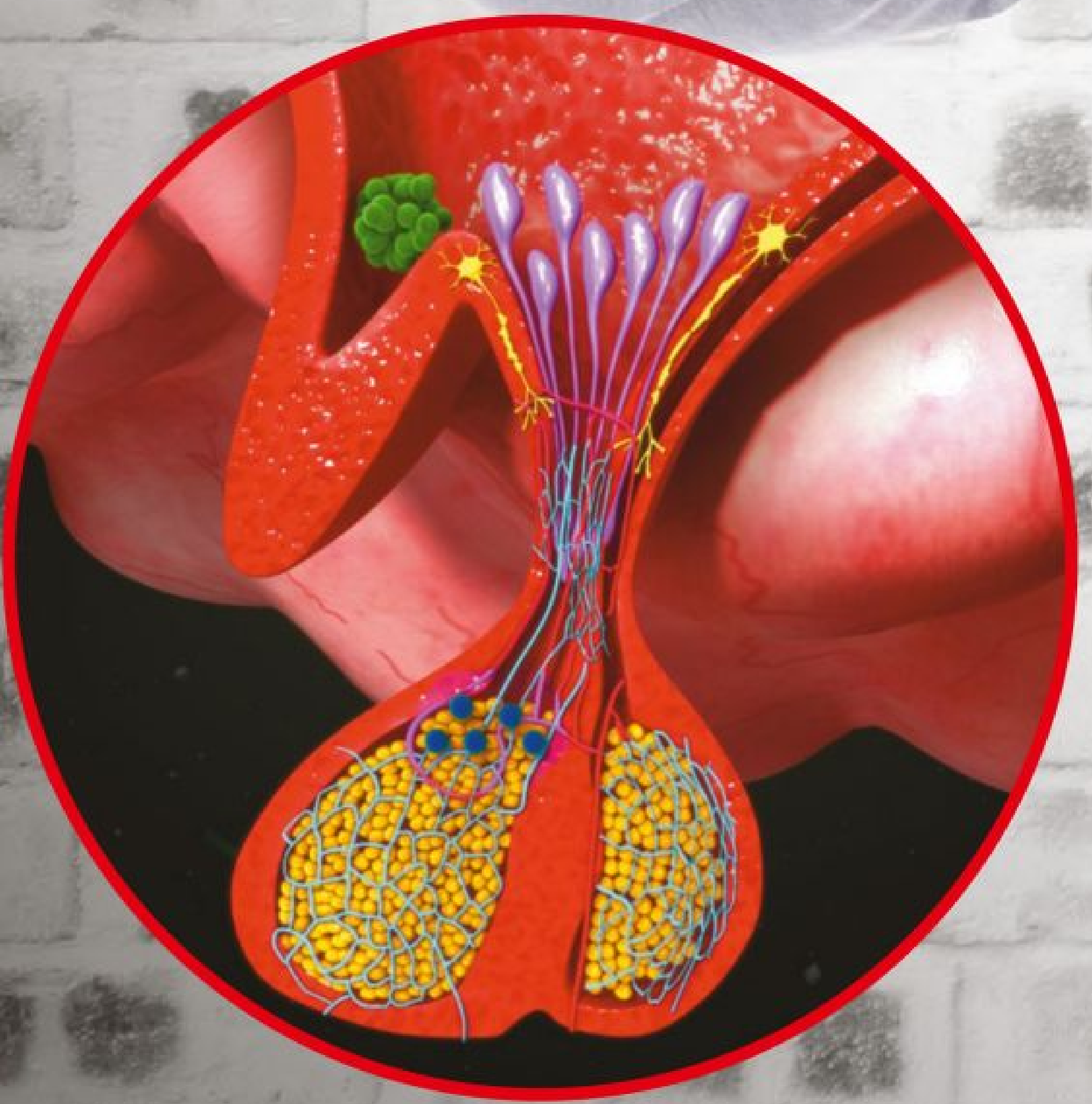
Breathing
An increased breathing rate can result in panic attacks and hyperventilation.

Heart rate
Raised heart rate and blood pressure can cause gradual damage to the cardiovascular system.

Hormones
Stress hormones like cortisol affect cells all over the body, including dampening the immune response.

Digestion
Changes in blood flow to the digestive system and different eating patterns can affect bowel function.

Reproduction
Fertility and libido can be affected by chronic stress in both men and women.



The pituitary gland is packed with hormone-producing endocrine cells

> *"It turns out that if we believe that stress is bad, it is more likely to do us harm"*

trigger for the biological response that puts the body into survival mode. From the hypothalamus, CRF hops a short distance through the bloodstream to the pituitary gland, where it triggers the release of a second, longer-range chemical message. Known as adrenocorticotropic hormone (ACTH), this molecule travels around the body in the bloodstream, reaching the kidneys, where it triggers the next step in the stress response process.

On top of each kidney is a hormone factory known as an adrenal gland, and within each is a compartment known as the adrenal cortex. The cells here produce glucocorticoids, the body's natural steroids. And it's these steroids that help the rest of the body to deal with stress. Cortisol interferes with insulin, helping to keep blood sugar levels up. It helps to balance the body's pH; it dampens the immune response; and it even affects the formation of memories.

Short-term stress is quickly corrected by the body, and, to prevent the cycle continuing forever, the cortisol also acts as an off switch. It feeds back to the brain, letting it know that the stress response has been fully activated, and helps to switch off the production of CRF and ACTH. But sometimes, stress can develop into a long-term, chronic problem.

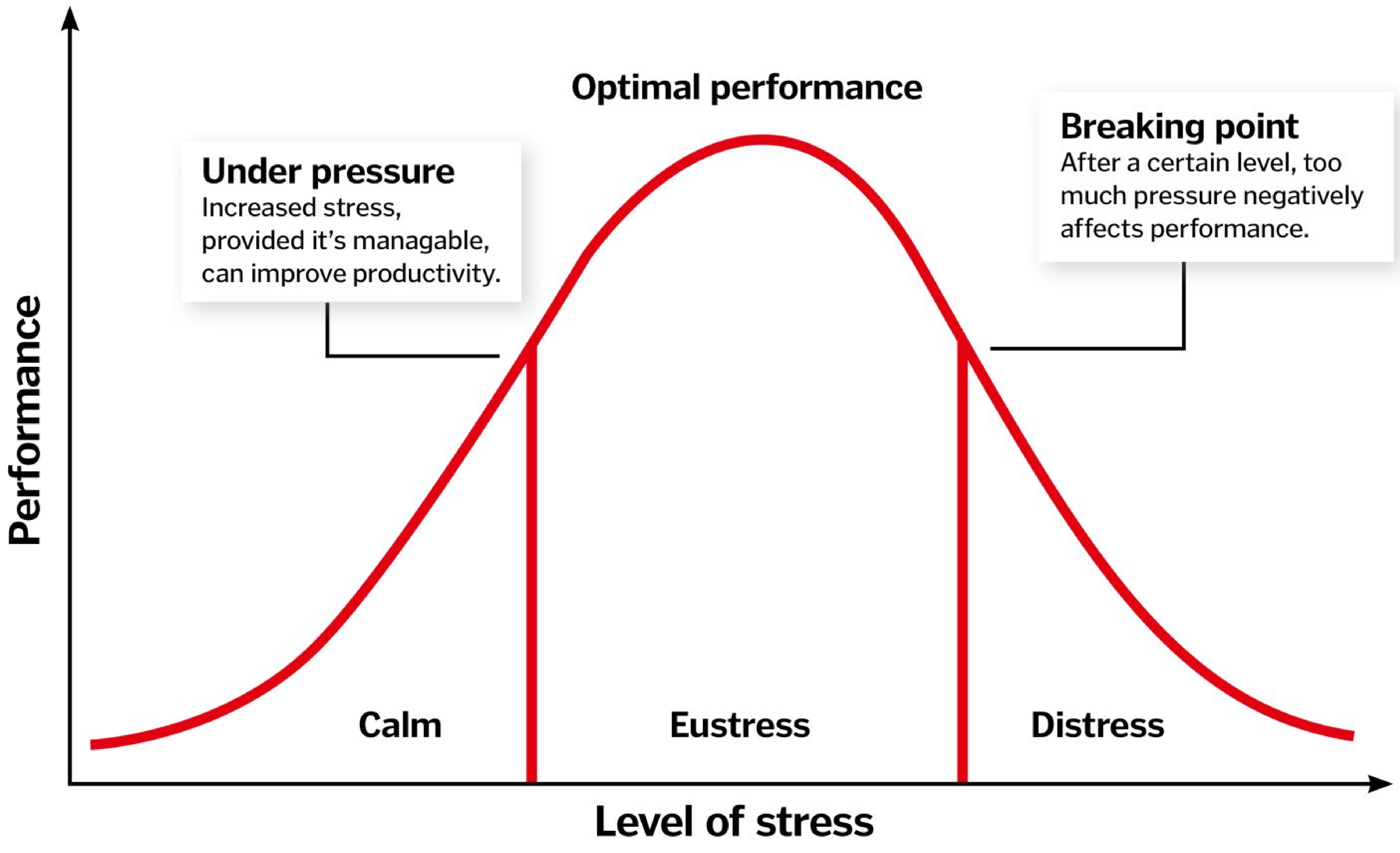
Humans are unique among animals (as far as we know) in that we think abstractly about the world and ourselves. Our enormous brains are a gift, but they can also lead to long-term stress as we worry over problems that just wouldn't occur to other animals, like work and money.

While the stress response has been honed by evolution to boost the chances of survival during short periods of increased environmental pressure, in the long term it can cause damage. Ultimately, it can lead to illness if left unchecked.

Exposure to stress during childhood, be it war, neglect or even divorce, can make people more likely to experience mental health problems as

Eustress vs distress

How can stress levels affect our ability to work?



Under pressure
Increased stress, provided it's managable, can improve productivity.

Breaking point
After a certain level, too much pressure negatively affects performance.

Good stress?

In 1936, endocrinologist Hans Selye wrote a letter to the scientific journal, *Nature*, describing the "general alarm reaction of the organism". He was one of the first people to identify and investigate biological stress. He continued his investigations, and after nearly 40 years of research, Selye came to the conclusion that stress wasn't all bad.

People had known for a long time that there's a link between 'stress' and productivity. In 1908, two researchers, Yerkes and Dodson, showed that there's a sweet-spot, where there's just enough pressure to encourage productivity, but not so much that it becomes too much for the person to handle.

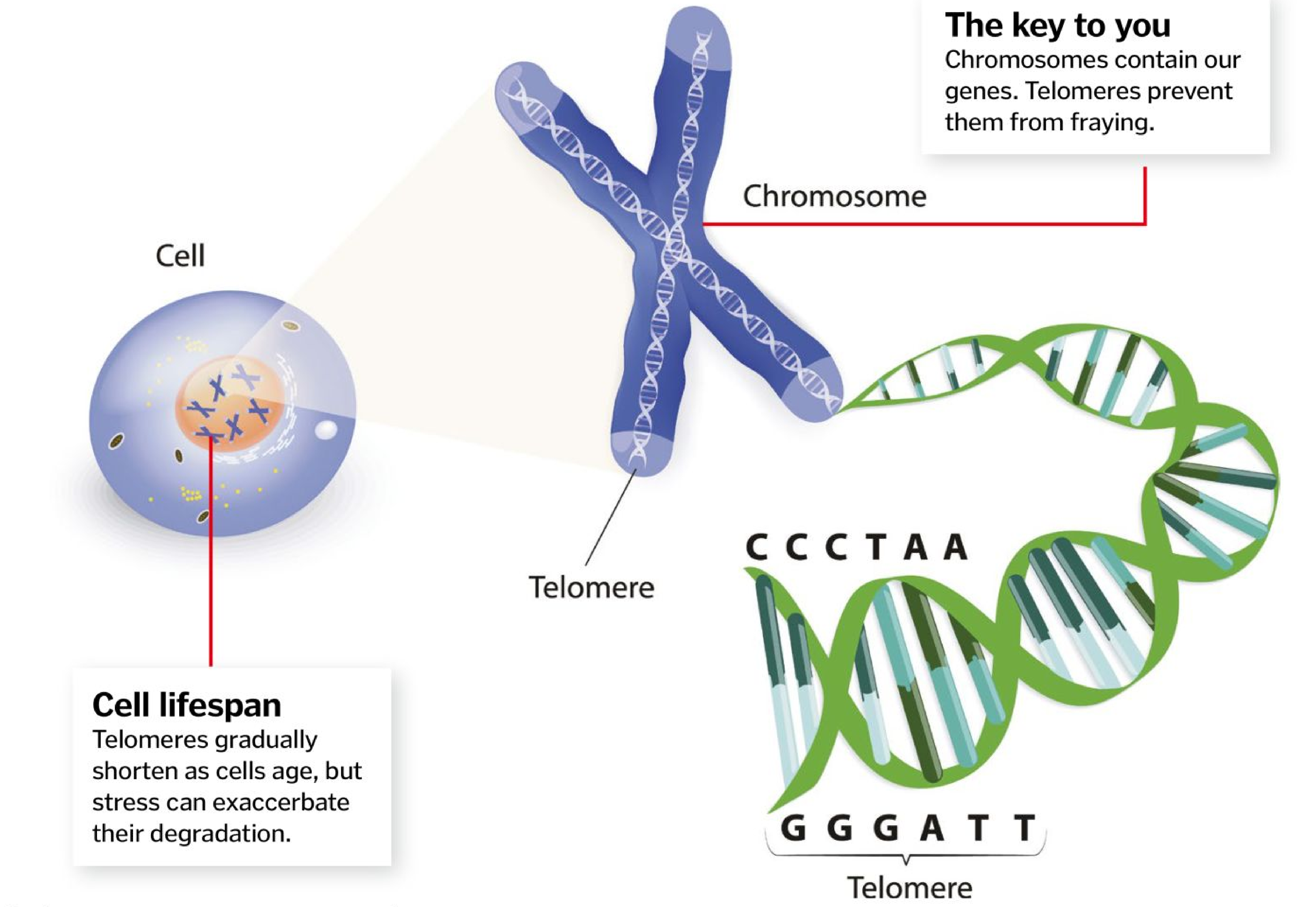
Selye was interested in the idea that the feeling of stress isn't so much about what happens to the body, but about how each individual reacts to the changes. In the 1970s, he introduced two new words, 'eustress' and 'distress', to describe what he saw. Eustress was beneficial stress, and distress was bad.

Stress-related damage

Long-term, or chronic, stress can be bad for our health, but it's challenging to pin down exactly why. Is it to do with poor lifestyle choices made under pressure, or is there something happening inside the body as a result of a prolonged stress response?

In 2004, a research team from the US published a paper in the journal *PNAS* that investigated what happens to our cells under stress. They looked at the genetic code, homing in on the protective caps that cover the ends of each chromosome. Known as telomeres, these structures shorten as cells get older. An enzyme called telomerase can replenish telomeres, but stress diminishes the supply of this regenerative enzyme.

The team studied a group of 58 women, and they found that the longer the women had been stressed, and the more stressed they felt, the more likely they were to have shortened telomeres – a sign that their bodies were feeling the strain. Exactly why this happens is not currently known.



The key to you
Chromosomes contain our genes. Telomeres prevent them from fraying.

Cell lifespan
Telomeres gradually shorten as cells age, but stress can exaccerbate their degradation.

Serious trauma or stress at an early age can cause telomeres to be shortened for life

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adults. During this period, the brain is still developing, and chronic stress can cause structural changes that affect the way that it functions. As adults, chronic stress puts strain on the heart and blood vessels, contributing to cardiovascular disease, heart attacks and strokes, and it can also damage the immune system.

During an acute stress response, immune cells are mobilised in case they need to fend off infection, but the stress steroid cortisol affects their function in the long term. In fact, drugs based on cortisol are used to dampen down the immune system in patients in need of immunosuppression.

Long-term stress can be a real problem. Not only does the response itself put pressure on the body, but coping mechanisms, including drinking and smoking, can all damage our insides. However, it's not just about the physical effects. 'Stress' is a loaded word, and recent research has been looking at how our perceptions of stress affect its impact on the body. It turns out that if we believe stress is bad, it is more likely to do us harm.

Studies in the US have shown that people who are stressed have an increased risk of dying. But – and this is critical – only if they believed that stress itself could cause them harm. In fact, people who were stressed but didn't believe it was bad for them had a lower risk of dying than those who were barely stressed at all.

The negative connotations of the word 'stress' bothered Hans Selye, who had first pointed out the stress response in the 1930s. Part of the trouble is that stress isn't just used to describe the body's response to challenging situations. In physics, strain is the change in shape or size of an object as a result of an external force, and stress is the internal force associated with it. The use of the same word links the two in people's minds.

Astonishingly, changing the way you think about stress seems to be able to change the effect it has on you. Seeing sweaty palms, increased heart rate and rapid breathing as signs that your body is trying to help you alters your internal response. Heart rate still increases, but blood vessels can stay relaxed, which is much better for the cardiovascular system. What's more, there's another component to the stress response that is often overlooked: oxytocin.

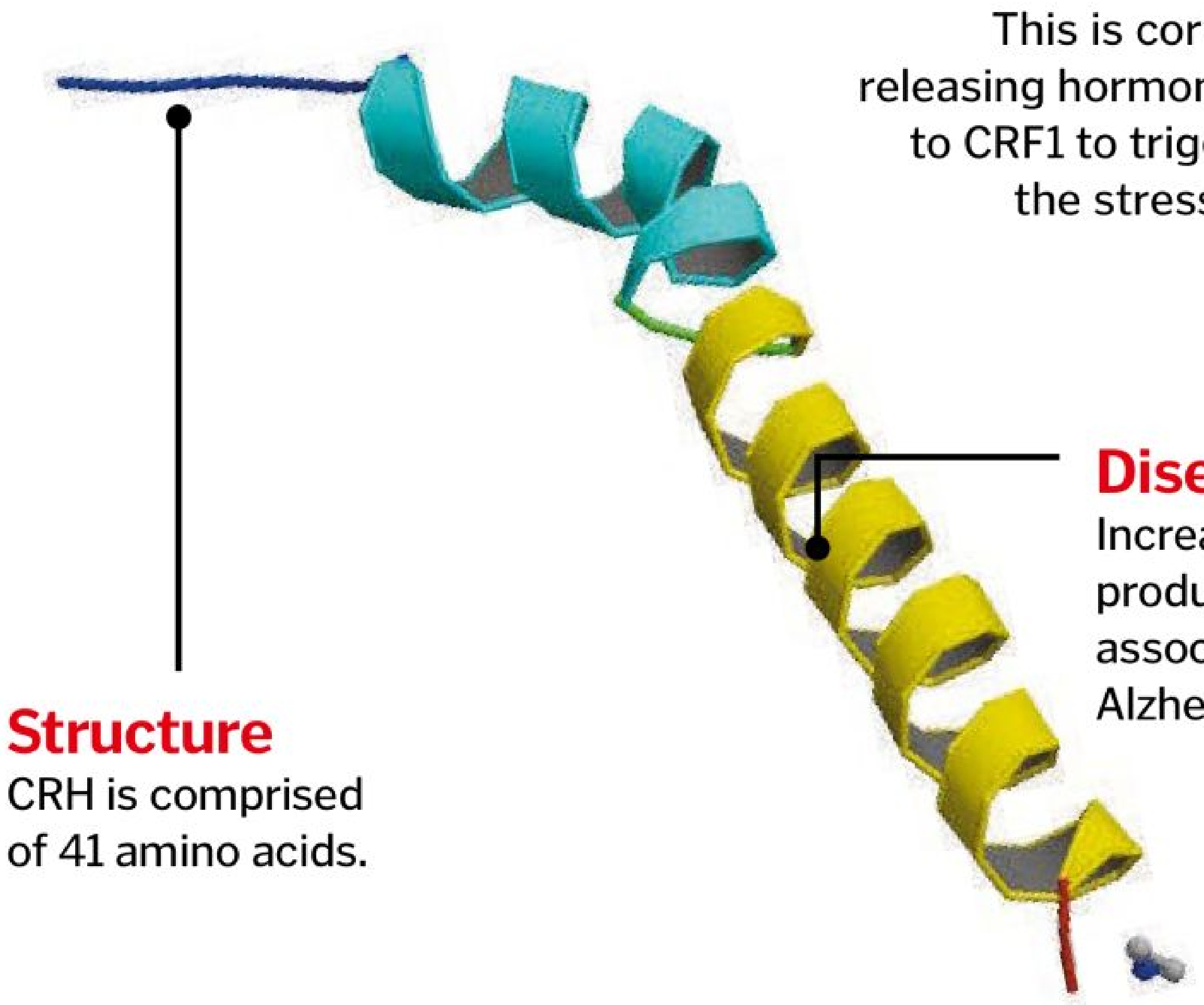
Popularly known as the 'cuddle hormone', oxytocin helps mothers to bond to their babies, and it's released by the brain when we are hugged. It is also produced during stress, helping us to seek social support. Oxytocin also helps by dilating blood vessels, lowering blood pressure and even helping to repair the heart.

While stress can feel unpleasant, it is there to help us deal with life's challenges. Believing in your body, and seeking support when things become too much, can help keep it under control.

Blocking stress molecules

The hypothalamus is the part of the brain responsible for kicking off the stress response, and it does this by producing corticotropin-releasing factor (CRF). This hormone travels to the nearby pituitary gland, where it tells the cells to begin pumping out adrenocorticotropic hormone (ACTH), which in turn tells the kidneys to make the stress steroid cortisol. One of the critical molecules in this pathway is known as CRF1: corticotropin-releasing factor receptor 1. It is the molecule that detects the CRF, and in 2013, scientists managed to work out its shape.

CRF1 sits on the surface of cells in the pituitary, and other structures in the body, and waits for CRF to arrive. When it does, the hormone sticks to the receptor and triggers molecular pathways that contribute to the stress response. Understanding its shape could help drug developers to design treatments that interfere with this interaction, stopping the hormone from slotting into its hole in the receptor, dampening the stress.



This is corticotropin-releasing hormone. It binds to CRF1 to trigger part of the stress response

Disease
Increased CRH production is associated with Alzheimer's.

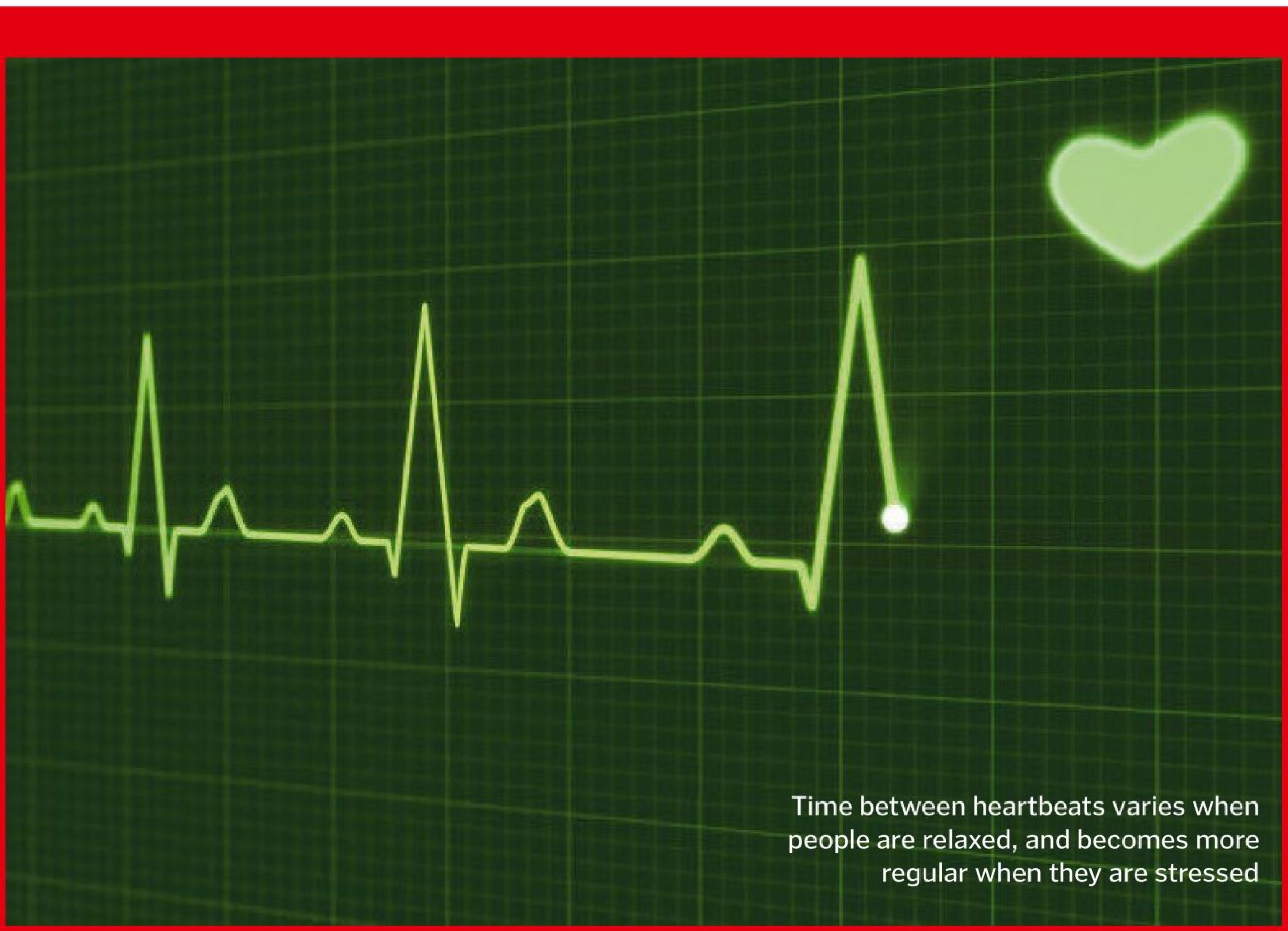
Structure
CRH is comprised of 41 amino acids.

Monitoring stress

The tech that can tell if you're having a tough time

There are several electronic gadgets that claim to be able to track your stress levels by tapping into your heart rate, breathing, skin conductance and blood oxygen. The idea is to help you to identify, and avoid, your stress triggers.

However, although some of the science behind the measurements they take is sound, it's not always easy to decipher what they mean. For example, the time between heartbeats varies less when you are stressed, but also when you are excited. A device that picks up on these changes won't be able to tell you which mood you are in unless it knows what else is happening around you.



Time between heartbeats varies when people are relaxed, and becomes more regular when they are stressed

Dealing with distress

There are several coping strategies that can help to combat stress

Exercise

The fight or flight response prepares your body for activity, so use up that nervous energy by exercising. Exercise also releases natural endorphins that boost your mood.

Believe in your body

Some studies have shown that stress is more harmful if you believe it is harmful. Trusting that your body is preparing you to cope helps to minimise damage.

Talk

People are social creatures, and the phrase ‘a problem shared is a problem halved’ didn’t come out of thin air. Seeking support can help to reduce stress.

Help others

Going out of your way to help other people when you are already stressed might seem counterintuitive, but it can help to give you purpose and perspective.

Take care of yourself

Some people seek comfort in damaging activities during times of stress, but nicotine, alcohol, food and other addictive substances don’t help the underlying problem.

Make a plan

Sometimes there are things you can’t change, but identifying the areas that you can and making a realistic plan to tackle them can help to guide you through stressful times.

Try mindfulness

Stopping and focusing on the present moment through meditation or mindfulness can help to change the way that you think and feel.

Keep a stress diary

Noting down the things that trigger feelings of stress can help you to prepare for them in the future.

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Types of headache

What's the difference between a migraine, a tension headache and a cluster headache?

There are dozens of different types of headaches, but according to the NHS, the most common is a 'tension' headache, which affects the whole of the head with a dull, tight pain associated with stress, dehydration and muscle tension.

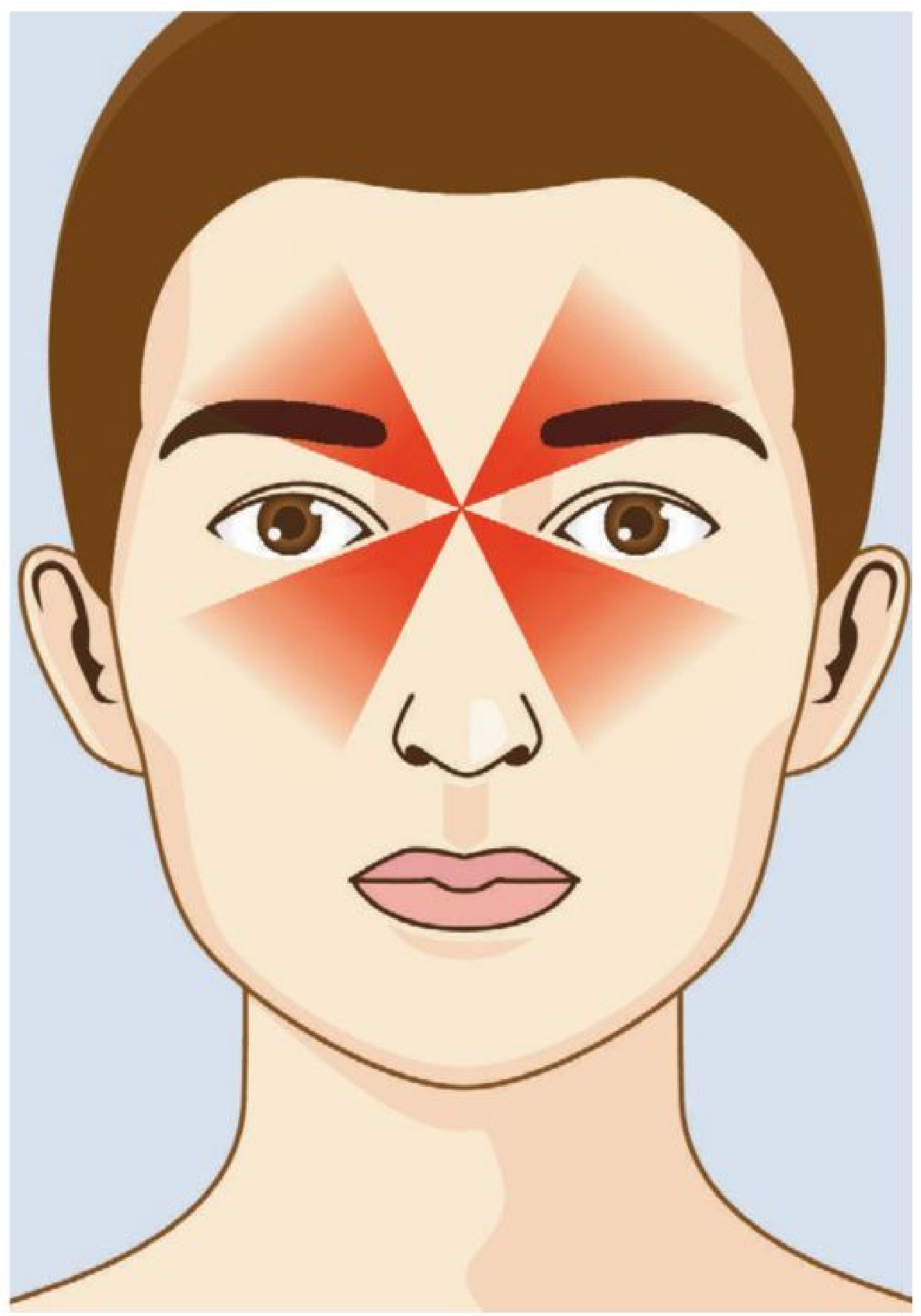
Migraines are more intense, and less common, striking one side of the head at a time and causing intense throbbing. They are thought to be linked to changes in nerve activity and blood-flow inside the brain. Hormonal changes can also cause headaches, and allergies and infections can cause pressure-related headaches due to congestion in the sinuses.

Rarely, a headache can be caused by something more serious. If the pain is sudden and intense, or is accompanied by a fever, rash, or changes in speech, memory or mobility, it's important to contact a doctor. Such headaches could be sign of a stroke or brain tumour.

Some people experience vision disturbance called an 'aura' before a migraine

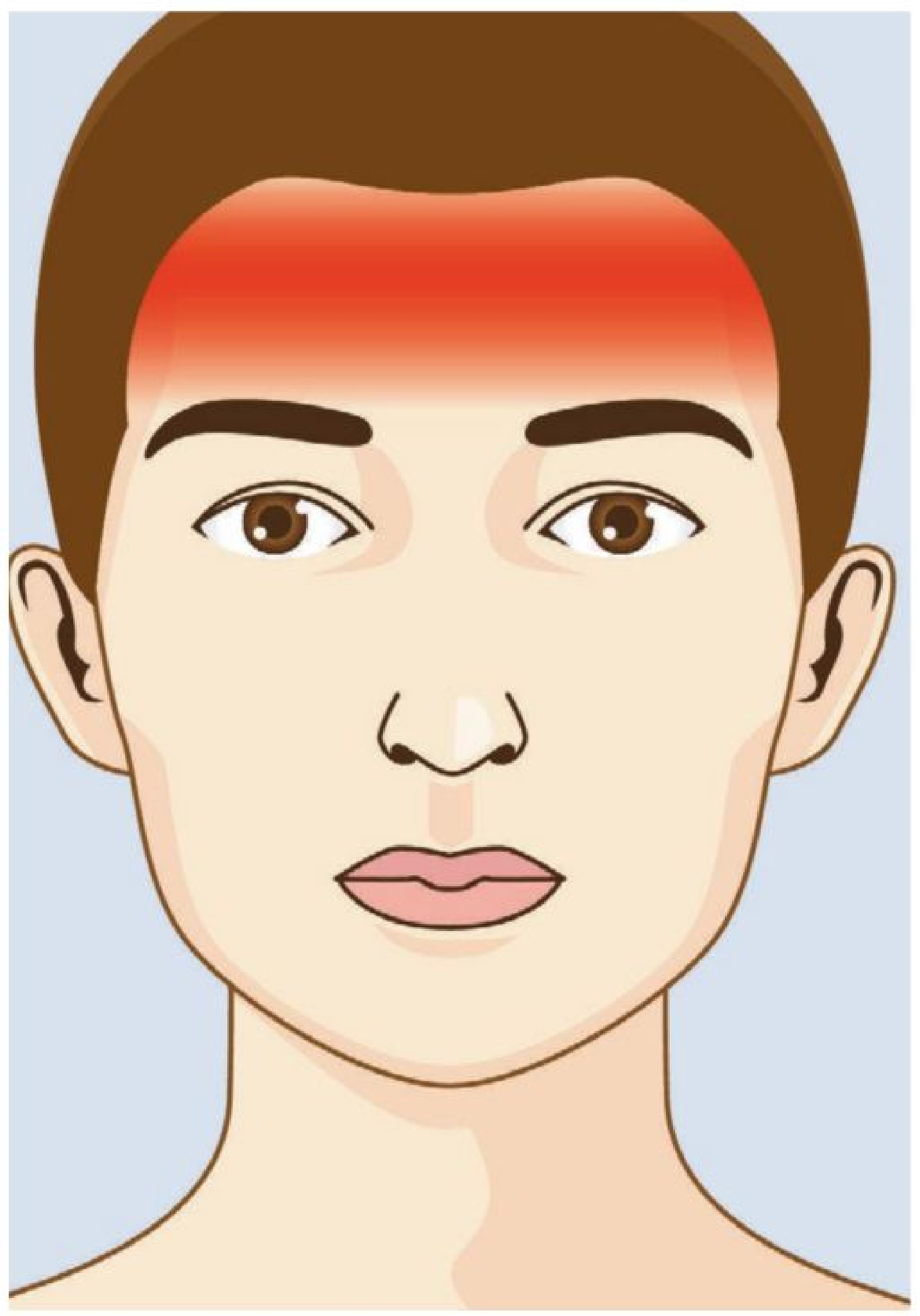
Top four headaches

Some of the most common headache types explained



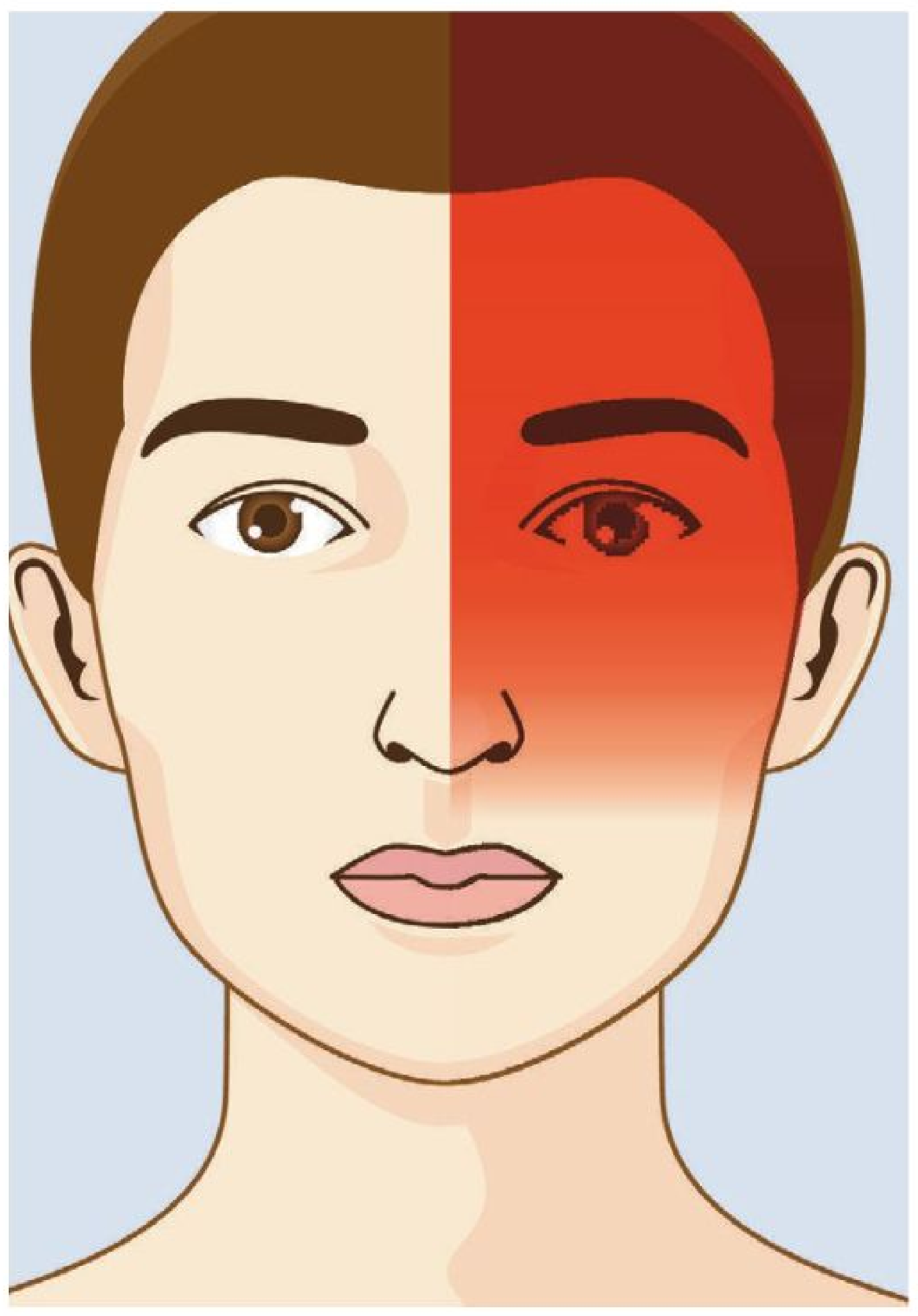
Sinus

Sinus headaches most often accompany an infection, and are linked to increased pressure either side of the nose and above the eyes due to mucus blockage.



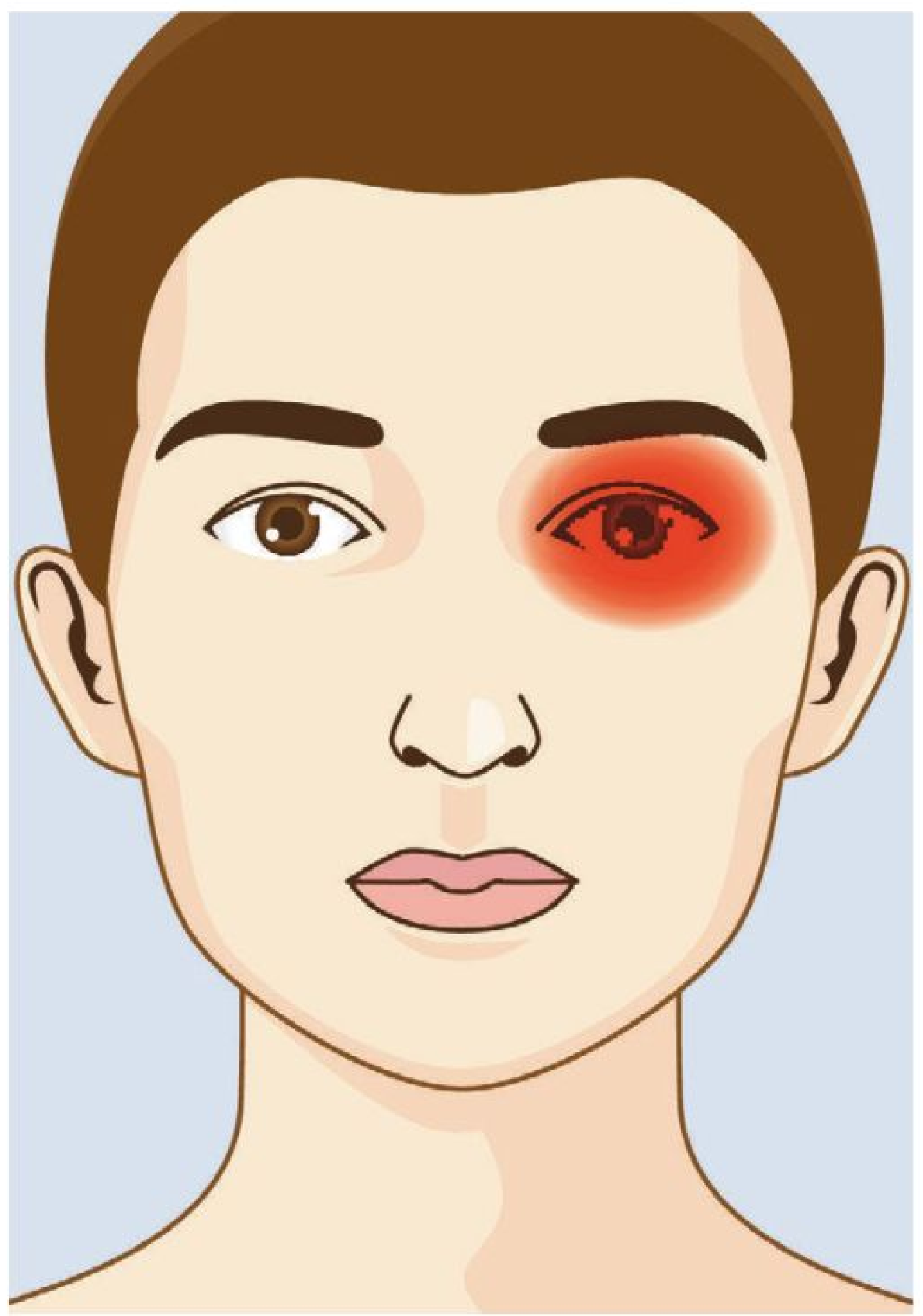
Tension

Tension headaches tend to affect both sides of the head, and consist of a tight feeling. They are thought to be related to stress, muscle strain and dehydration.



Migraine

Characterised by intense, throbbing pain on one side of the head, migraines can affect people's vision or make them feel sick or sensitive to noises and lights.



Cluster

Cluster headaches affect one eye, and are associated with severe pain, nasal congestion and tear production. This type of headache tends to recur several times.

How clean are your teeth?

Discover how dental disclosing tablets reveal the hidden plaque that coats your gnashers

Your teeth might look squeaky clean after you've finished your morning brush, but plaque can be difficult to spot. It's a sticky film of bacteria and sugar that is constantly forming across the surface of the enamel and below the gumline, and if left long enough it can harden to form a substance called tartar, which is extemely difficult to remove.

Dental disclosing tablets can reveal the plaque that you might have missed when brushing. These chewable pills contain vegetable dyes that stick to the plaque and stain it a bright colour, making the deposits easier to see. The bacteria in the plaque live in a web of molecules called a matrix, and the dye becomes trapped in this network, revealing the areas of the teeth that still need to be cleaned. They are available at chemists and can be used at home to help you to spot problem areas that you might need to pay special attention to when you clean your mouth.

Research has shown that people tend to end up with cleaner teeth after a dental disclosing tablet makes them aware of the plaque that still remains after their usual brush.

Disclosing tablets reveal the plaque that you missed when brushing your teeth

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Anatomy of facial expressions

Does it really take more muscles to frown than to smile?

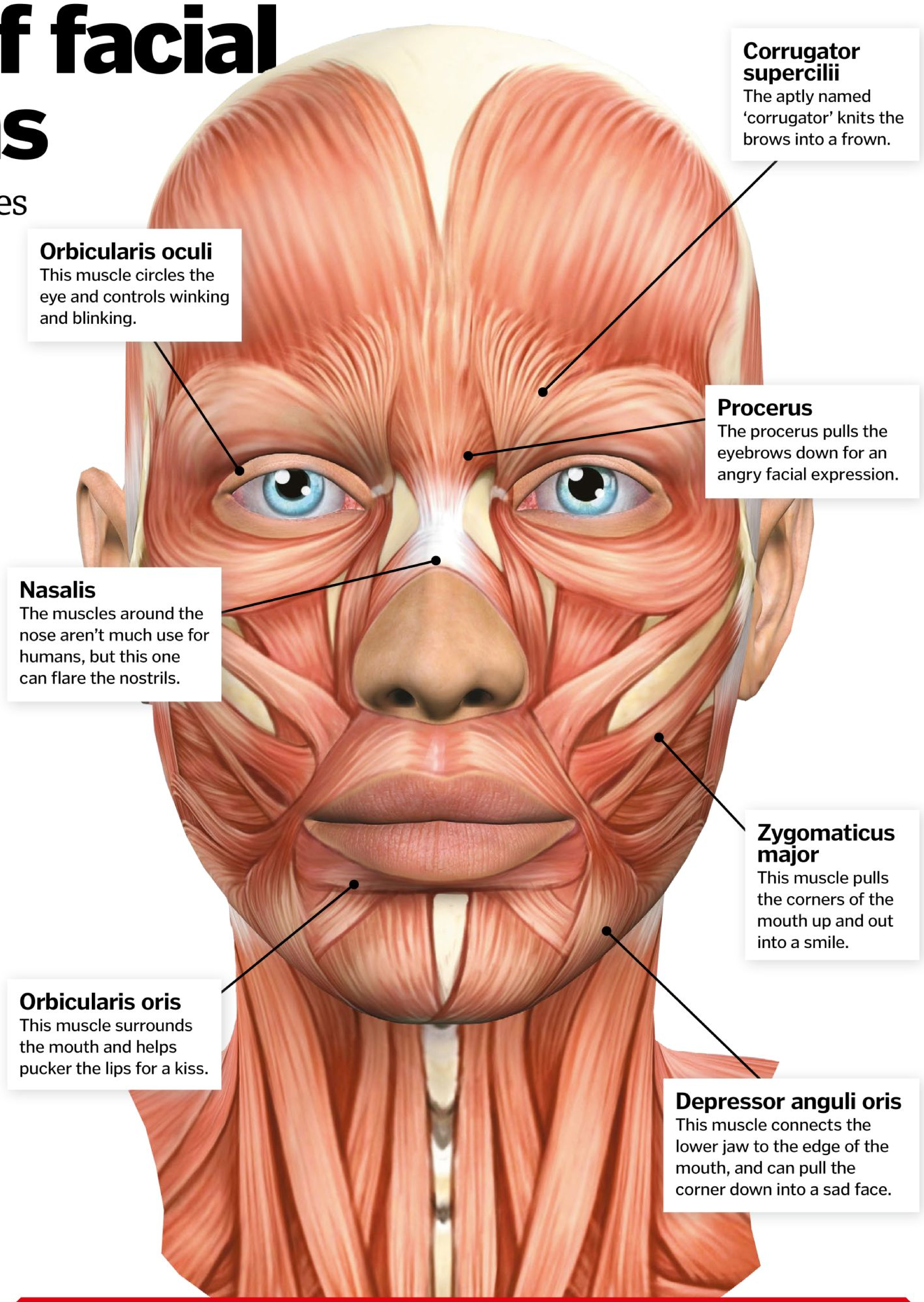
The 43 muscles of the face sit just under the skin. At one end, they are attached to bone, or sheets of tissue known as fascia, and, unlike any other muscles in the body, they join directly to the skin at the other end.

We can sort our facial muscles into three groups: the orbital group, the nasal group and the oral group. Together, they enable us to make four core expressions: happy, sad, afraid and angry, and over 20 combined expressions.

There are two muscles in the orbital group – the orbicularis oculi, which surrounds the eye socket, and the corrugator supercilii, which controls the eyebrow. The first is responsible for blinking and winking, and the second contracts to pull the eyebrows together into a frown.

We don't have a lot of control over the movement of the muscles around our nose, but the nasalis is the biggest, and with help from the depressor septi it flares the nostrils. The procerus runs from the top of the nose to the forehead, and it can pull the eyebrows down.

Finally, there are the oral muscles. The two major ones are the orbicularis oris, which surrounds the mouth and contracts to purse and pucker the lips, and the buccinator running under the cheekbone. There are also two groups of smaller muscles, the upper and the lower groups, which control the fine movements of the facial tissue to form smiles and frowns.



Corrugator supercilii
The aptly named 'corrugator' knits the brows into a frown.

Orbicularis oculi
This muscle circles the eye and controls winking and blinking.

Procerus
The procerus pulls the eyebrows down for an angry facial expression.

Nasalis
The muscles around the nose aren't much use for humans, but this one can flare the nostrils.

Zygomaticus major
This muscle pulls the corners of the mouth up and out into a smile.

Orbicularis oris
This muscle surrounds the mouth and helps pucker the lips for a kiss.

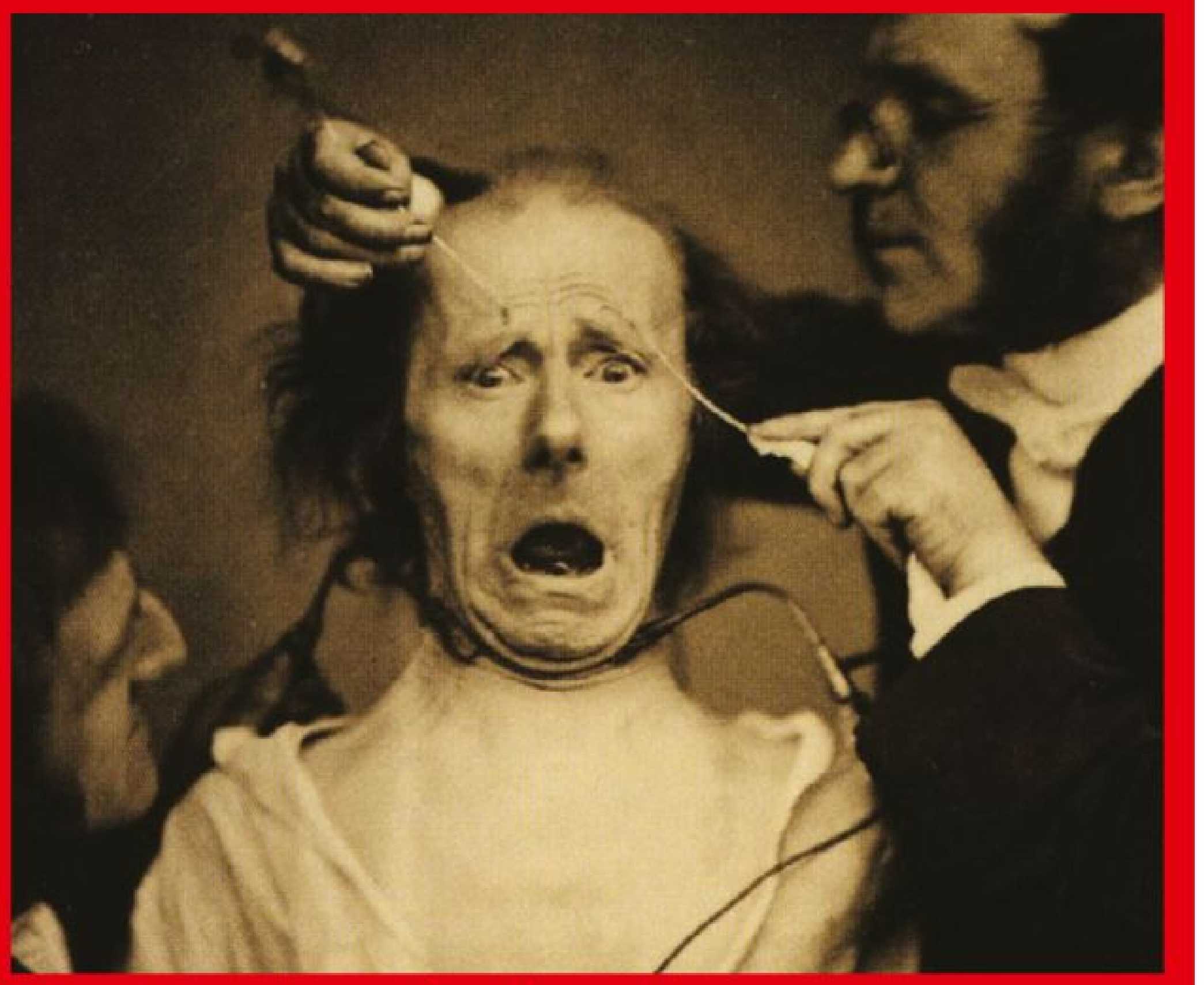
Depressor anguli oris
This muscle connects the lower jaw to the edge of the mouth, and can pull the corner down into a sad face.

Smile
It takes a minimum of five pairs of muscles to pull the lips into a smile.

Frown
It takes at least three pairs of muscles to pull the lips into a frown.

Deciphering the face

Benjamin Amand Duchenne was a French physiologist in the 19th century, and his macabre experiments attempted to reveal the muscles responsible for different facial expressions. He wired test subjects up to galvanic probes, which delivered small electric shocks through the skin to the underlying muscles. He tried his experiment on five test subjects: a girl, a young man and woman, and an older man and woman. He captured pictures of the expressions made when different parts of the face were stimulated. Charles Darwin was so taken with the images that he later used them in his own experiments to find out whether people could read the emotions of the test subject just by looking at the expressions that their faces were pulling.



This photo shows Duchenne's experiment in action

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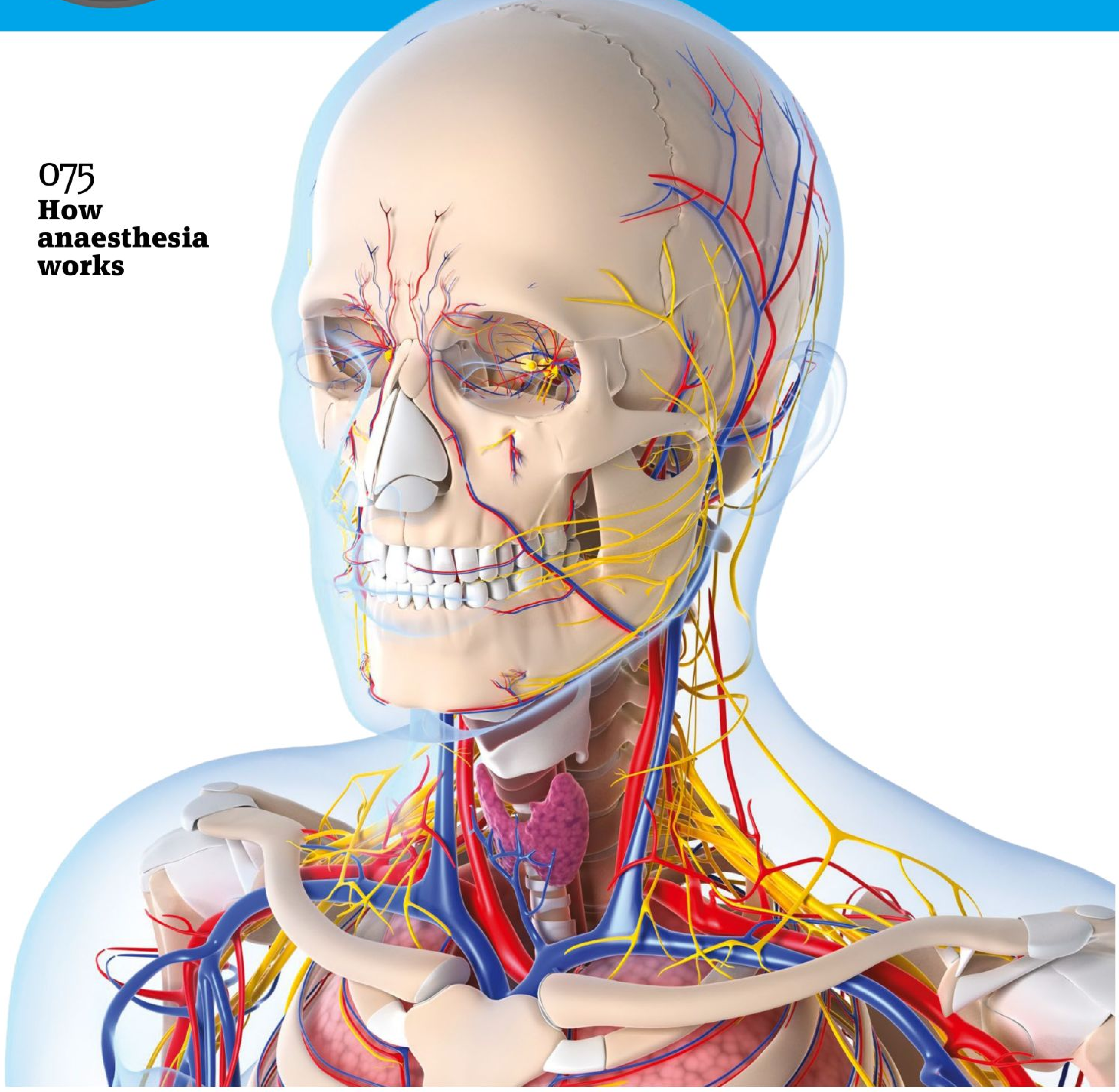
CHEMISTRY



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13 CHEMISTRY LIFE HACKS

A little science knowledge goes a long way when it comes to solving these everyday problems

A common complaint in science classrooms is that nothing you learn in your school chemistry class will be useful in everyday life, but we've got 13 chemistry life hacks that prove otherwise. We'll show you how getting to grips with freezing points can cool your drink in record time, how electrolysis can clean your silver jewellery, and how understanding acids and bases can de-stink your fridge. We've got a trick for removing rust with an everyday acid, a way to use your knowledge of solubility to get a red wine stain out of your carpet, and a food chemistry hack for reviving stale cookies.

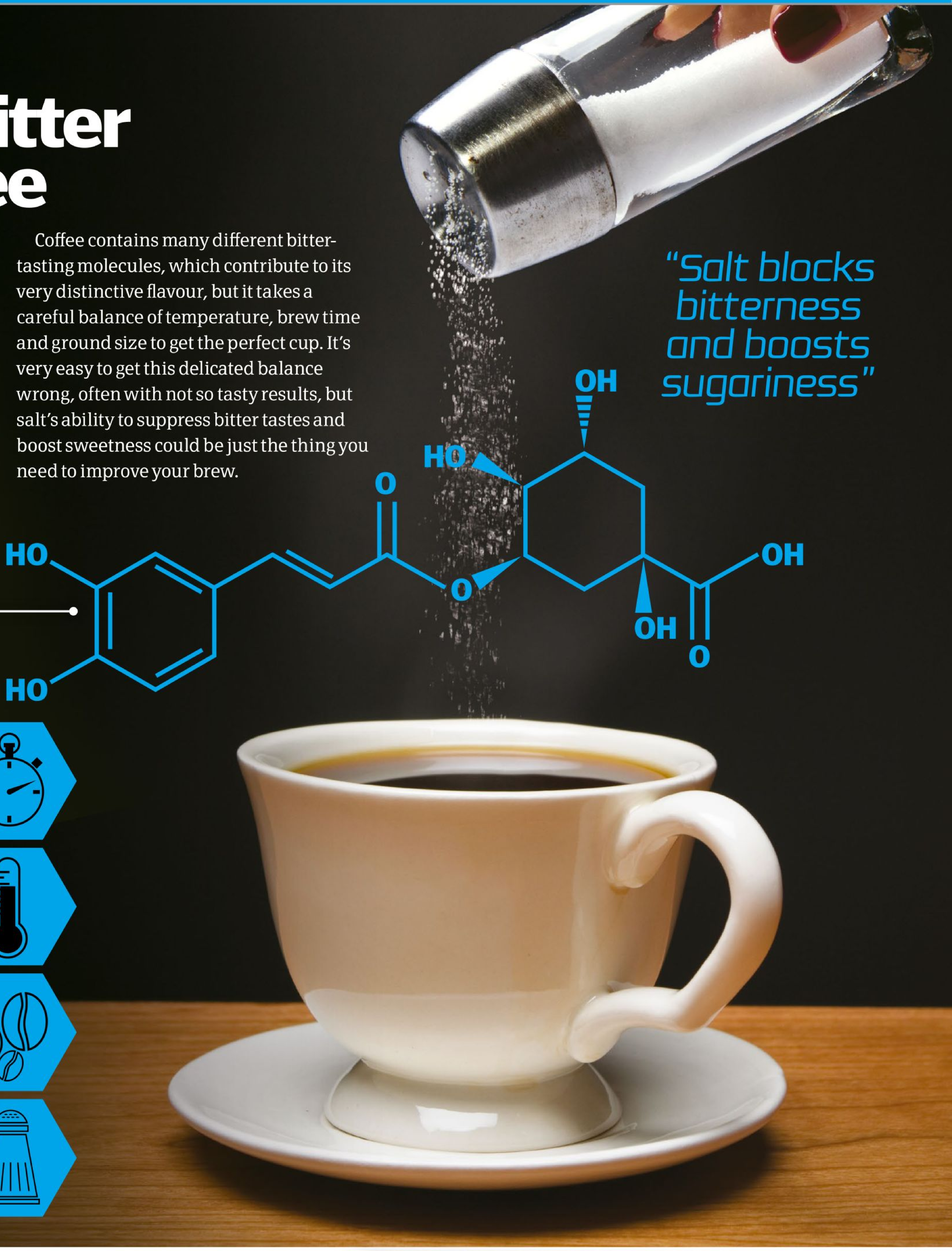
Chemistry explains what matter is made of, the properties it has, and how different molecules interact in the world around us. And understanding the chemistry behind common home conundrums will make your food taste better and save you a ton on expensive cleaning products and time.

HACK #1 Fix bitter coffee

It's well known that salt makes food taste good, but in 1997, scientists found out why. In a study published in the journal *Nature*, they asked volunteers to drink a bitter urea drink with added sucrose for sweetness, or sodium acetate for saltiness. Sugar didn't improve the taste on its own, but salt did, and when the two were combined, the drink tasted even sweeter. It seems salt blocks bitterness and boosts sugariness.

Coffee contains many different bitter-tasting molecules, which contribute to its very distinctive flavour, but it takes a careful balance of temperature, brew time and ground size to get the perfect cup. It's very easy to get this delicated balance wrong, often with not so tasty results, but salt's ability to suppress bitter tastes and boost sweetness could be just the thing you need to improve your brew.

> "Salt blocks bitterness and boosts sugariness"



Coffee chemistry

The smell and taste of coffee are the result of a complex mix of molecules

Bitter molecules
Coffee beans naturally contain chlorogenic acids, which break down into bitter quinolacetones, phenyl indanes and melanoidins when the beans are roasted. These are responsible for the flavour.

Brew time
The longer the coffee grounds are in contact with water, the more the bitter compounds enter the drink and the stronger it tastes.

Water temperature
The temperature of the water affects how well the bitter molecules are extracted from the coffee. Ideally, it should be between 90 and 96 degrees Celsius.

Grind size
The finer the grind, the more surface area is in contact with the water and the faster the bitter molecules will dissolve.

Salt
Adding salt counteracts the bitterness and increases sweetness. Minerals in hard water affect the taste too.

HACK #2 Remove rust with cola

Phosphoric acid is the sour ingredient that balances the sugary taste of the world's favourite fizzy drink, but it's got another use — it's an industrial-strength rust remover capable of transforming reddish iron (III) oxide into yellow-toned ferric phosphate. To repair a rusty object, simply cover it in cola and let the acid get to work. Not only will it help to remove the rust, the layer of iron phosphate will provide some rust proofing, protecting against future corrosion.

Iron reacts with oxygen in the presence of moisture, creating red-toned iron oxide

HACK #3

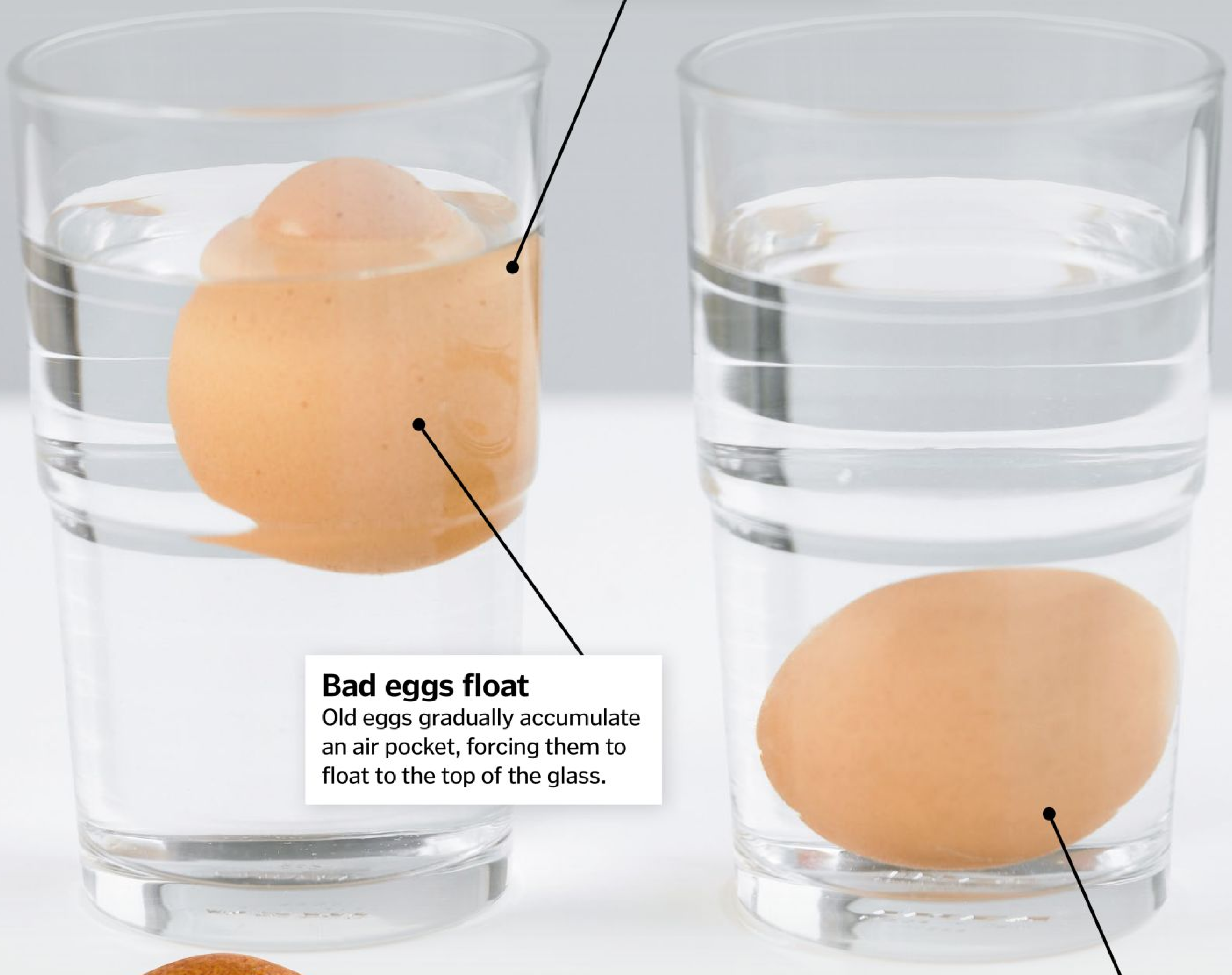
Check if eggs are fresh

Fresh eggs are full to the brim with yolk and white, but the shell is porous to allow the developing chick to breathe. Over time air leaks through the protective coating and a bubble starts to form. For a sure-fire way to tell if your eggs are fresh, simply put them in a bowl of water and see if they sink or swim.

The freshest eggs are best for frying or poaching because the yolk is round and the white is thick. These should sink to the bottom of the bowl and lie down horizontally on their side. Slightly older eggs are better for hard boiling because the white is thinner and they are easier to peel. These eggs will tip up on their edge, sitting upright in the water but not quite floating. The oldest eggs will rise to the top of the water. These are best thrown away as they are not really fit to eat.

Fresh or not?

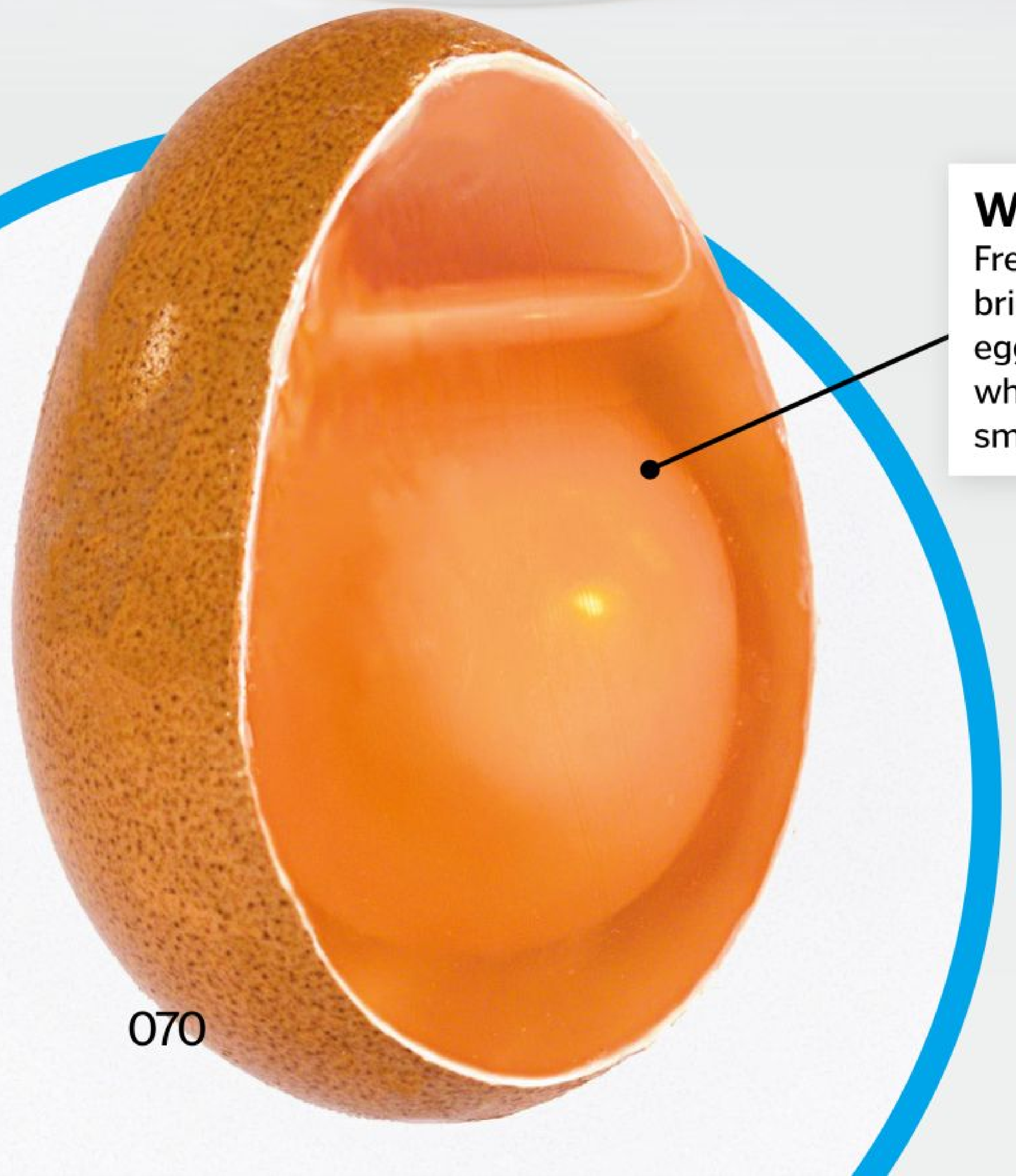
How to quickly identify a good egg without having to crack the shell



Leakage
Eggshells allow gasses to pass through and, as the egg gets older, air leaks in.

Bad eggs float
Old eggs gradually accumulate an air pocket, forcing them to float to the top of the glass.

Good eggs sink
Fresh eggs are crammed full of yolk and white and sink to the bottom of the glass.



What's inside?
Fresh egg yolks are bright and round, older eggs have a runnier white, and rotten eggs smell of sulphur.

> *"Egg shells are porous to allow developing chicks to breathe"*

Cool your drink with salt

HACK #4

There's a layer of liquid water on the surface of ice, and when you add salt it dissolves into this layer. This dissolved salt slows down the rate at which water molecules can attach to the ice beneath but doesn't affect the rate at which molecules detach from the solid. The overall effect is more molecules detaching and becoming liquid, allowing the ice to melt without raising the temperature.

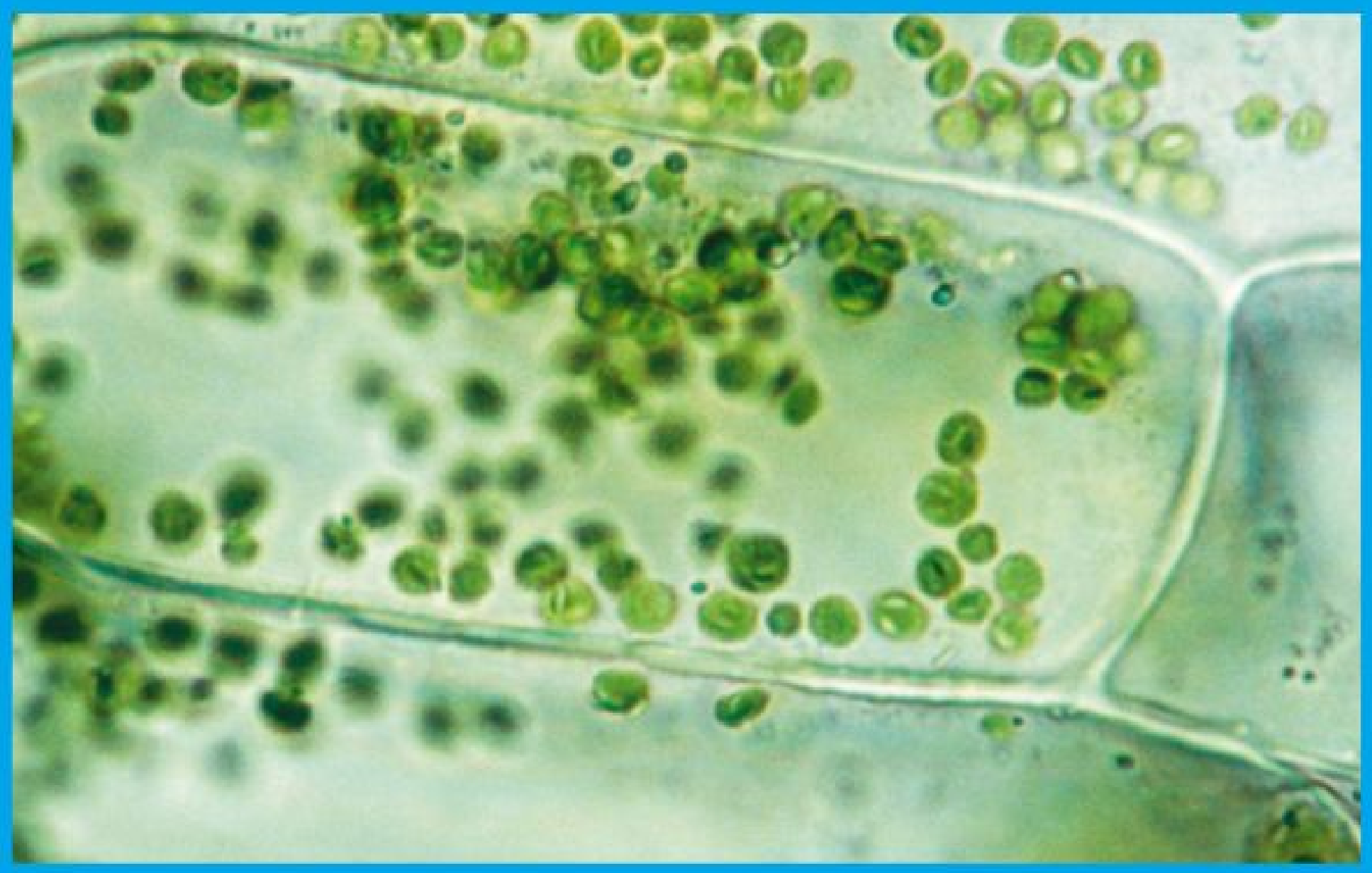
If you put a can into an ice bucket only parts of the surface touch the chilly solid, but add salt to the mix and the chilly liquid will completely surround your can, cooling it down much faster.

Gritters coat the road in salt to lower the freezing point of ice and snow

Keep your veg green

HACK #5

When you first plunge veggies into boiling water, air bubbles expand, making their green colour appear more intense, but over time the vibrant shade turns yellow. This is because a magnesium ion in the green pigment, chlorophyll, is swapped for hydrogen in the presence of acids released during cooking. To prevent this from happening, minimise cooking time, use lots of water to dilute the acid, and don't add vinegar or lemon until you're ready to eat.



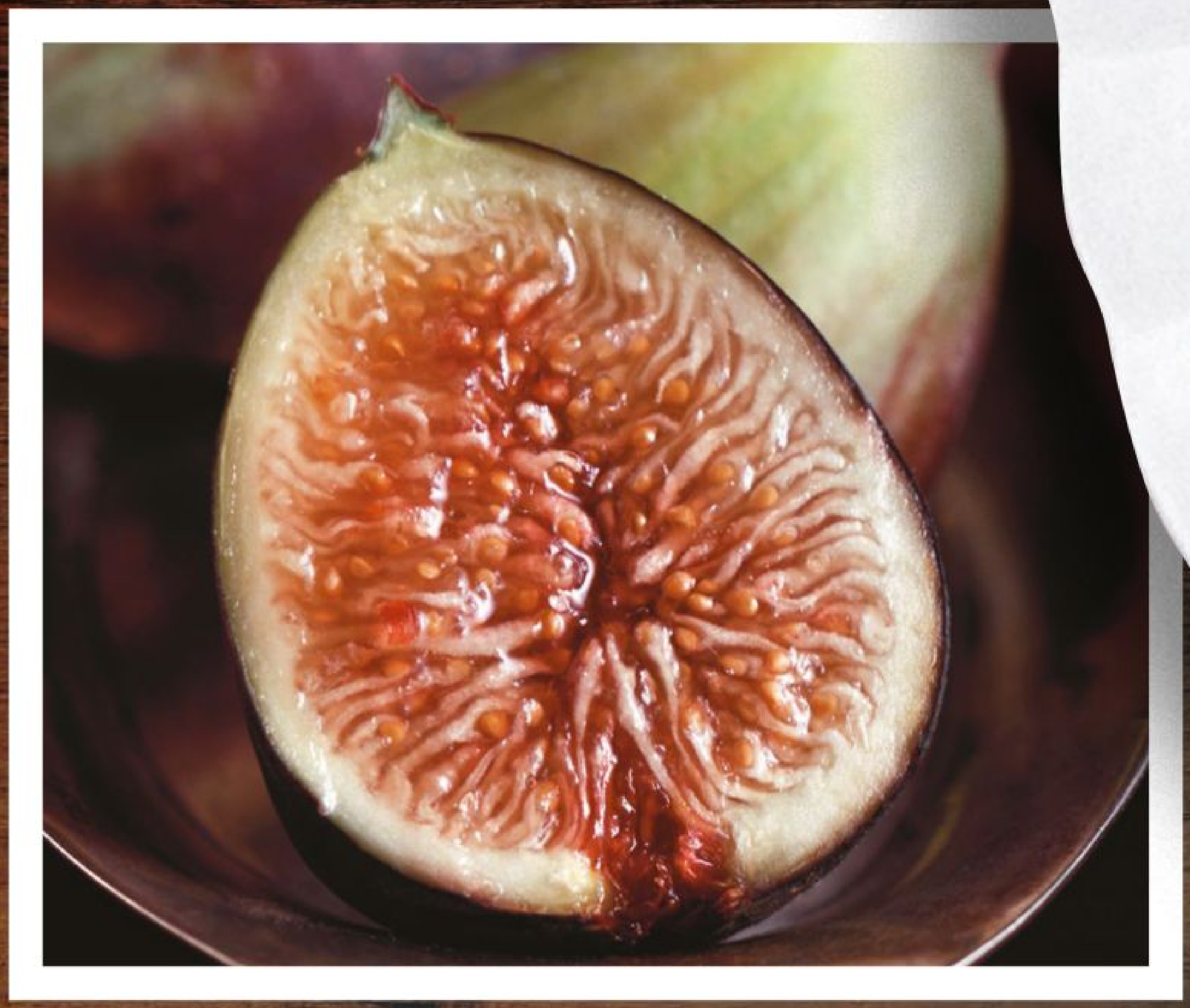
Plant cells are stuffed with chloroplasts, which contain the green pigment chlorophyll

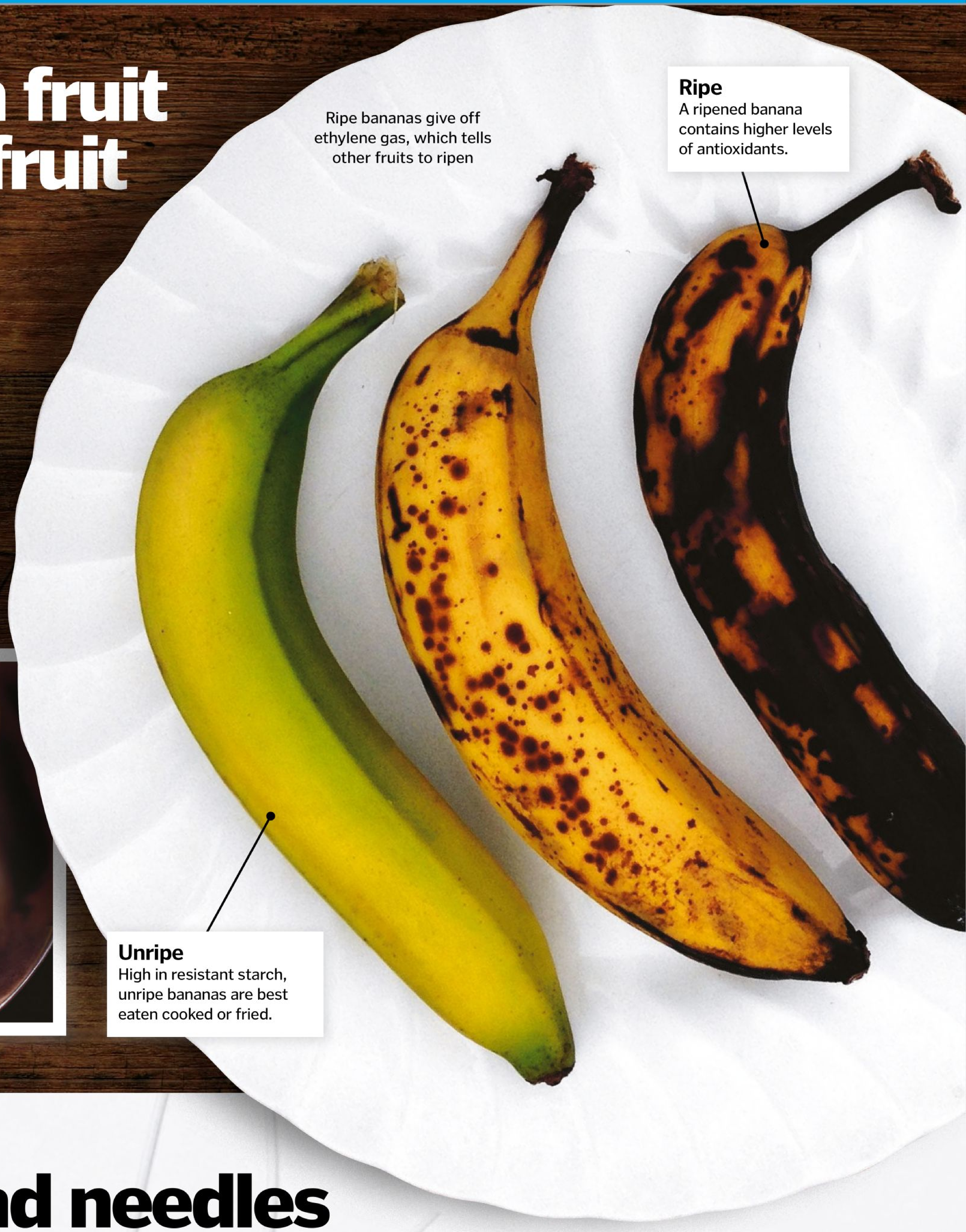
HACK #6

Ripen fruit with fruit

Ripe fruits like tomatoes and bananas give off ethylene, or ethene. This natural chemical is also known as 'fruit-ripening gas' and has been used for centuries to artificially speed up fruit ripening. The Egyptians made holes in figs to let the gas out, people in ancient China burnt incense to release ethylene, and modern transport vehicles pump the gas over fruit on their way to the supermarket to ensure it's ready to eat on arrival. To use this trick at home, just place an ethylene-producing fruit like a banana, fig, mango, nectarine or plum next to an unripe fruit and it'll be ready to eat in no time.

A favourite of the ancient Egyptians, figs encourage other fruits to ripen





Ripe bananas give off ethylene gas, which tells other fruits to ripen

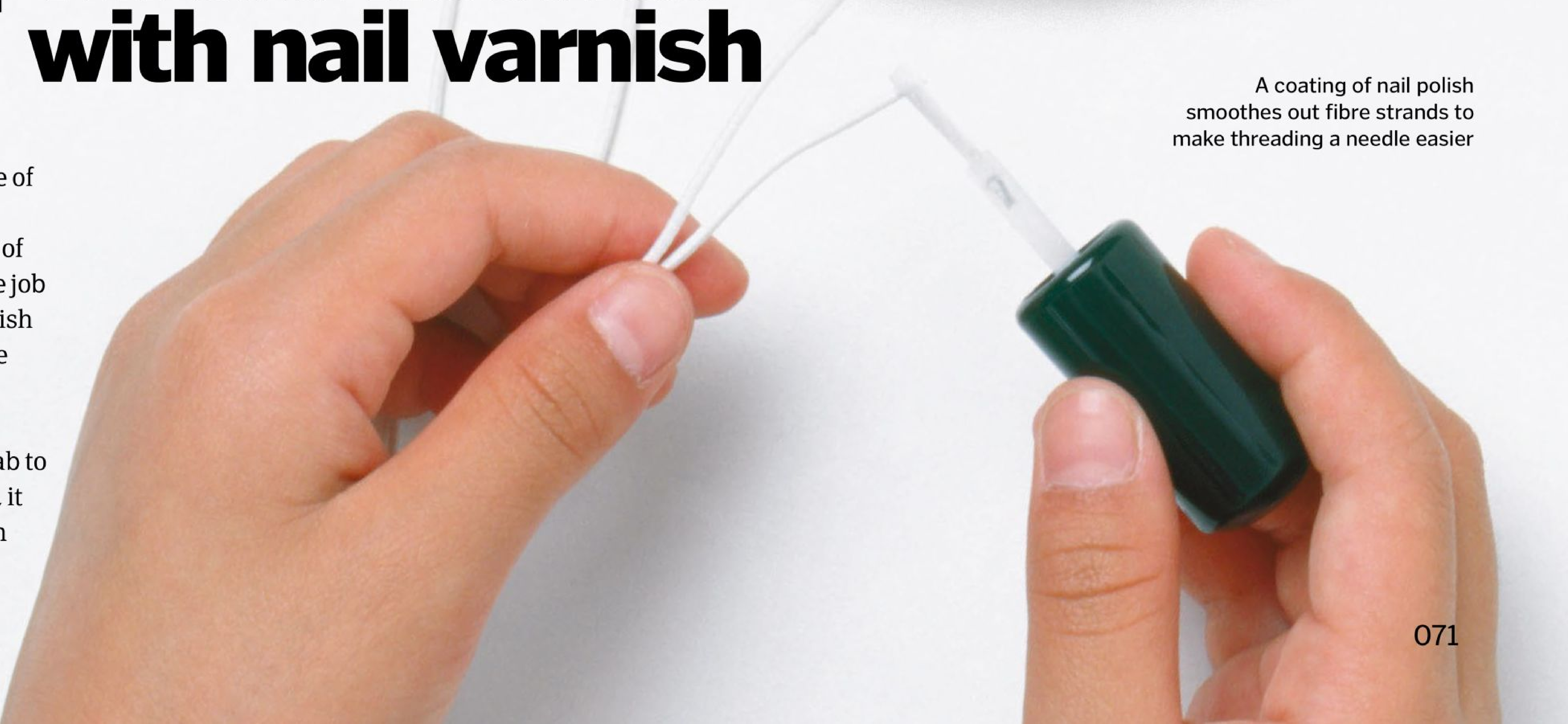
Ripe
A ripened banana contains higher levels of antioxidants.

Unripe
High in resistant starch, unripe bananas are best eaten cooked or fried.

HACK #7

Thread needles with nail varnish

Poking a soft, frayed thread through the eye of a needle can be a challenge, but a bottle of nail varnish makes the job much easier. Nail varnish contains nitrocellulose suspended in a fast-evaporating solvent — when you apply a dab to the end of your thread, it rapidly forms a smooth film over the strands.



A coating of nail polish smoothes out fibre strands to make threading a needle easier

BICARB HACKS

Humble baking soda is all you need to solve these common household problems

Refresh tarnished silver

HACK #8

Silver can lose its lustre over time, becoming coated in a layer of black silver sulphide, but there's a chemistry trick to gently restore its shine. The first thing to do is line a bowl with aluminium foil and then add a spoon of baking powder, a pinch of salt and some hot water. The bicarbonate of soda will react with the foil, stripping away the layer of aluminium oxide on the surface, while the salt allows electrons to move between the foil and the silver, creating a small electrical current. The silver gains electrons and the aluminium loses them and, in the process, the sulphur transfers from your cutlery to the foil.

The black tarnish on old silverware is silver sulphide

Make bread without yeast

HACK #9

The bubbles that make bread dough light and airy are most often made by yeast, a single-celled organism that consumes sugar and produces carbon dioxide, but you can still make a decent loaf without it. Soda bread is a traditional quick bread with four key ingredients: flour, bicarbonate of soda, salt, and an acid like buttermilk, milk, yogurt or cream of tartar. The soda reacts with the acid to make carbon dioxide, allowing the bread to rise. But be careful with the proportions; the bread will collapse if the bubbles become too big, and too much bicarbonate of soda can make the mix taste soapy.

Bicarbonate of soda can replace yeast to make dense, rustic soda bread

Banish fridge odours

HACK #10

Bicarbonate of soda has the chemical formula $NaHCO_3$, and it's got some special properties. It is amphoteric, which means it can react with both acids and bases, and this makes it a great DIY fridge deodouriser. Lots of bad food smells are caused by acids and alkalines produced as food starts to go off; sour milk contains lactic acid, bad meat contains rancid fatty acids, and rotten fish contains alkaline trimethylamine oxide. When bicarbonate of soda reacts with these, it forms a sodium salt, water and carbon dioxide, neutralising the odour. An open box inside the fridge door should help to keep bad smells at bay.

Bicarbonate of soda can neutralise bad smells by reacting with acids and alkalis

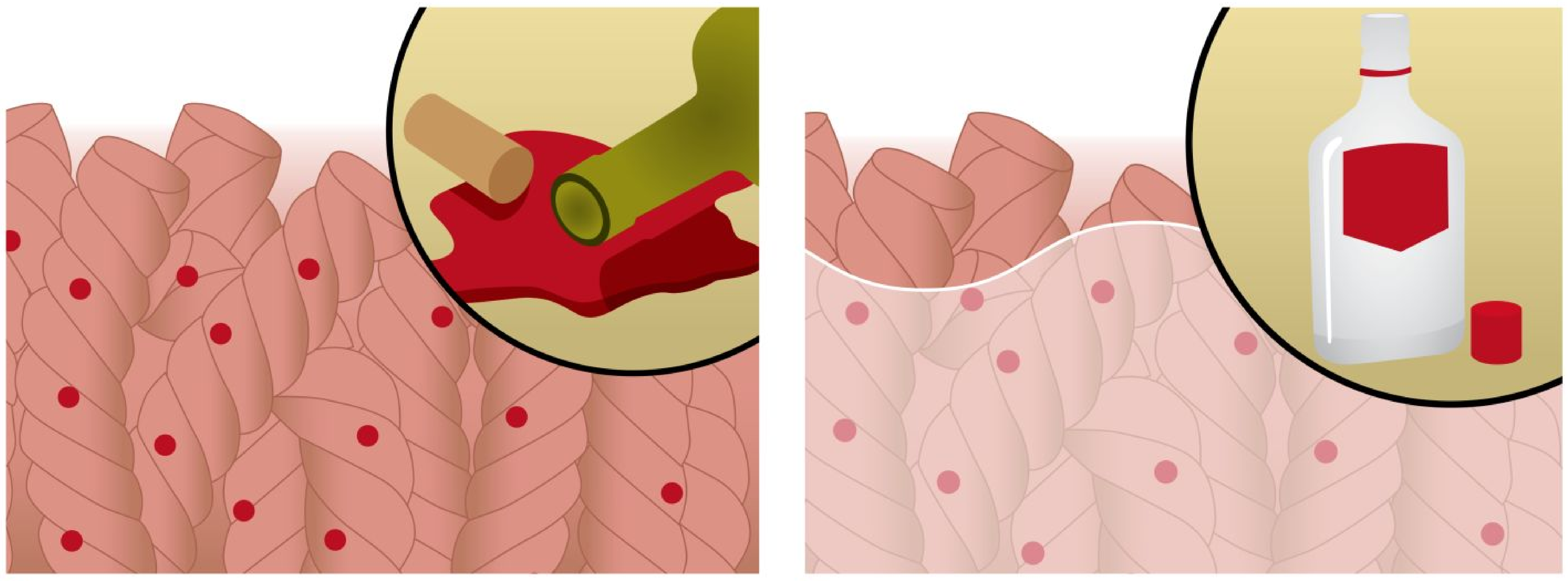
HACK #11 Remove wine stains with vodka

The distinctive colour of red wine is created by pigments called anthocyanins and pyranoanthocyanins, which are formed when anthocyanins interact with molecules made by alcohol-producing yeasts. Their chemical structure makes them a little bit hydrophobic ('water hating') and a little bit hydrophilic ('water loving'), meaning that they dissolve in both organic solvents, like alcohol, and aqueous solvents, like water.

White wine is often used to remove red wine stains because it contains a mix of alcohol and water, helping to capture the pigment molecules and pull them out of the fabric, but a better option to quickly remove a stain is to use something stronger. Clear spirits like vodka, white rum or gin contain a higher percentage of alcohol, dissolving the pigment molecules even more effectively. Just keep dabbing at the stain and adding more alcohol until the colour begins to fade away.

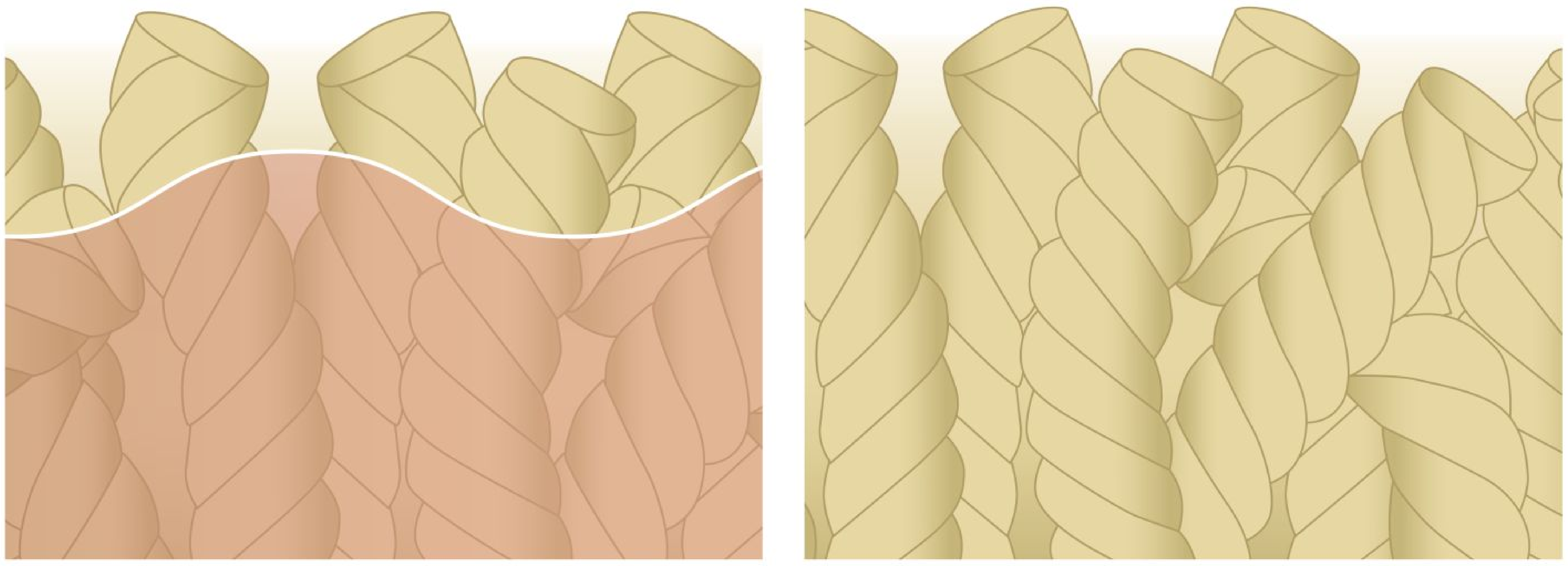
Carpet stain chemistry

How to dissolve red wine pigments before they stain your fabrics



1 Stain
The anthocyanin pigment molecules in red wine get stuck between carpet fibres, staining the fabric pink.

2 Add alcohol
The mix of water and alcohol in a high-proof spirit like gin dissolves the pigment molecules.



3 Dab
The dissolved pigment can be removed from the carpet by dabbing at the stain with a cloth.

4 Rinse
Rinse any alcohol residue away with water and your carpet will be as good as new.

> *"Vodka, white rum or gin will dissolve red wine pigment molecules more effectively"*

Descale your kettle with vinegar

HACK #12 Hard water contains dissolved calcium hydrogencarbonate, which breaks down into insoluble calcium carbonate, also known as limescale, when it's heated. To get rid of it, mix one part vinegar or lemon juice with three parts water and boil the kettle, then let the hot mixture sit overnight. The acid will react with the limescale, forming soluble calcium salts that can be tipped away in the morning.

A scanning electron microscope image showing crystals of limescale inside a kettle

Soften cookies with bread

HACK #13 Bread, cake and cookies contain moisture, which transforms starch from crystals into a disorganised gel, but as moisture moves away from the starch, they go hard and stale. All you need to do to refresh baked goods is restore that moisture. Simply put your hard cookie in a bag with a piece of fresh bread and it should soften up in no time.

The starch inside cookies turns to orderly crystals as they dry out

© Getty; Thinkstock; Illustration by Jo Smolaga

What is micellar cleansing water?

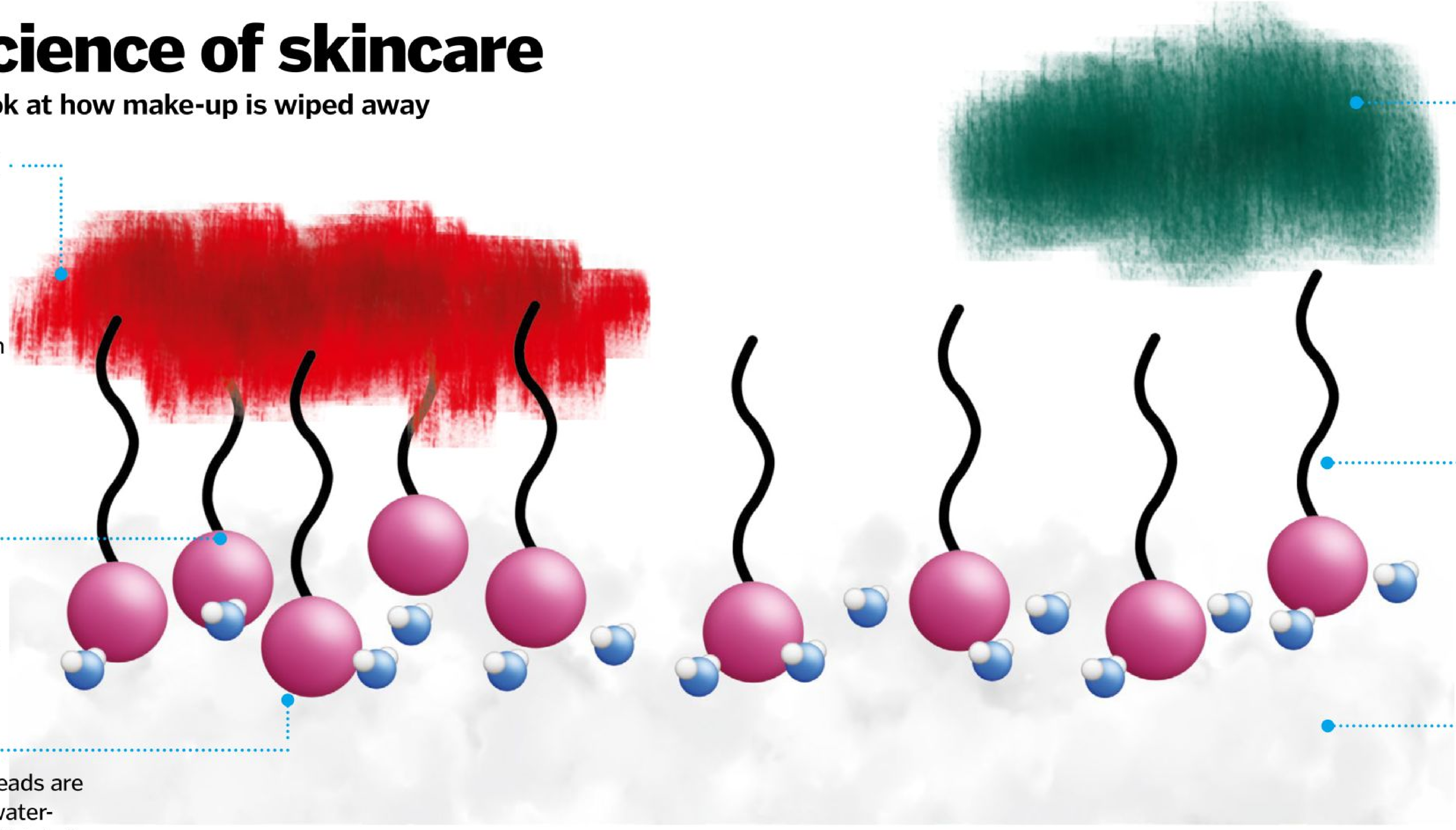
The chemistry behind the gentlest make-up remover on the market

Micellar cleanser takes advantage of water-loving and water-hating molecules

Micellar cleanser has us marvelling at how this water-like solution removes make-up so easily. A micelle is a made up of molecules that have water-loving (hydrophilic) heads and water-hating (hydrophobic) tails. They form as little spheres, with the heads facing outward and the tails pointing inward. When you pour the micellar solution on the cotton pad, the hydrophilic heads are attracted to the cotton, leaving the hydrophobic tails pointing outward to attract oil and make-up. The tails form a ring around the oil, pulling it gently away from your skin and onto the wipe like a magnet.

The science of skincare

A close-up look at how make-up is wiped away



Strong bond
As the bond between the water and hydrophilic head is strong, the micelles stay with the cotton pad, pulling the make-up away.

Cluster
A group of micelles form a cluster around the oil molecules.

Head
The hydrophilic heads are attracted to the water-soaked pad and stick to it.

Oil
The tail is attracted to the oily make-up and wraps itself around the molecules.

Tail
The hydrophobic tails hate water so point away from the pad.

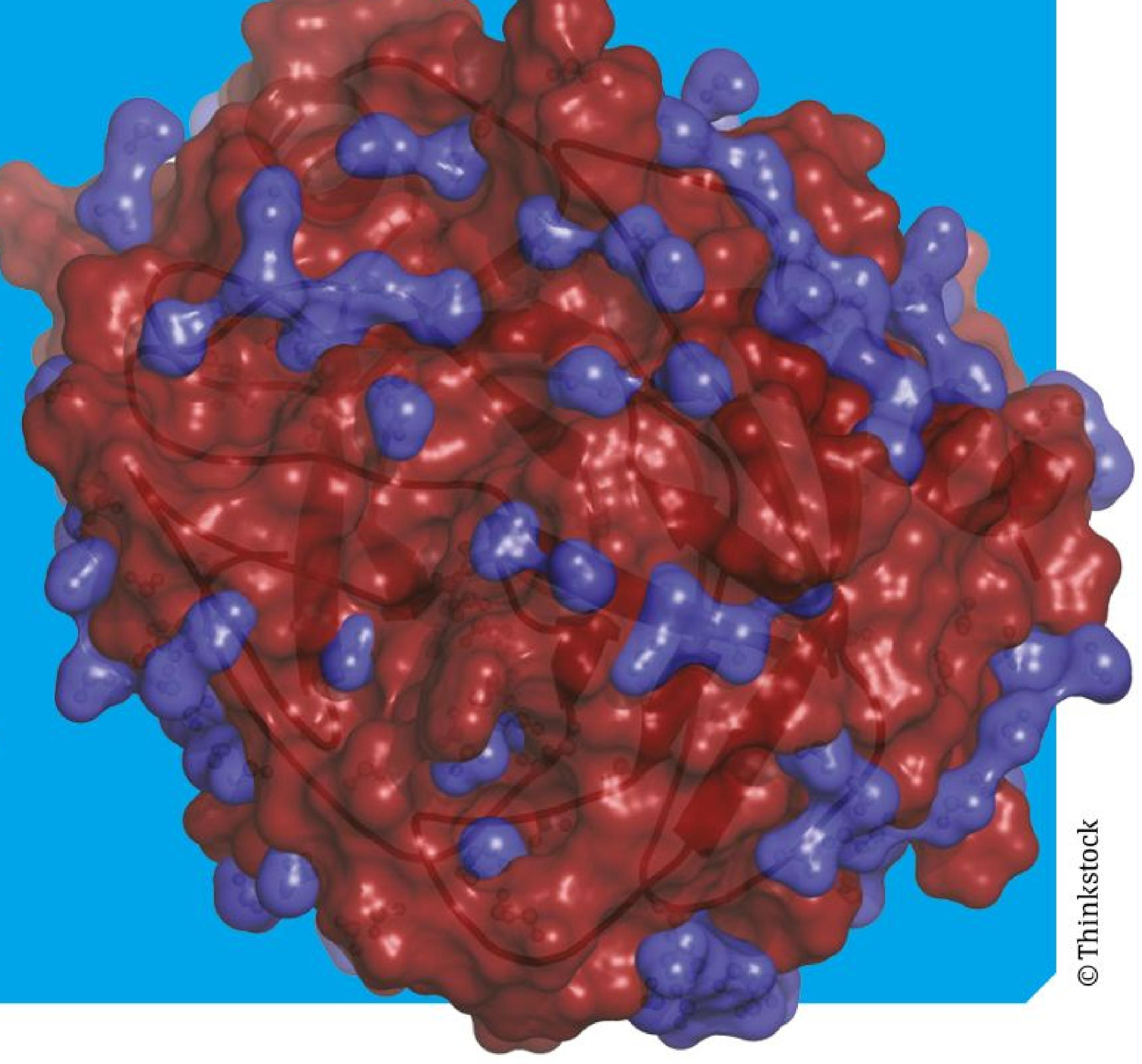
Absorption
Cotton soaks up the cleanser, which is a solution of water and the micelle molecules.

How enzymes keep you alive

The proteins that speed up your body's chemical reactions

Enzymes increase the speed of reactions inside cells by lowering the energy-activation requirement for molecular reactions. Molecules need to react with each other to reproduce, but our bodies provide neither the heat nor the pressure required for these reactions.

Each cell contains thousands of enzymes, which are amino acid strings rolled up into a ball called a globular protein. Each enzyme contains a gap called an active site into which a molecule can fit. Once inside the crack, the molecule – which becomes known as a substrate – undergoes a reaction such as dividing or merging with another molecule without having to expel energy in a collision with another molecule. The enzyme releases it and floats on within the cell's cytoplasm. The molecule and active site need to match up perfectly in order for the sped-up reaction to take place. For example, a lactose molecule would fit into a lactase enzyme's active site, but not that of a maltase enzyme. Interestingly enough, enzymes don't get used up in the process, so they can theoretically continue to speed up reactions indefinitely. ✲



Enzymes such as trypsin work to help break down proteins

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How anaesthesia works

By interfering with nerve transmission these special drugs stop pain signals from reaching the brain during operations

Anaesthetics are a drug used to prevent pain associated with surgery. They fall into two main categories: local and general. Local anaesthetics can be either applied directly to the skin or injected. They are used to numb small areas without affecting consciousness, so the patient will remain awake throughout a procedure.

Local anaesthetics provide a short-term blockade of nerve transmission, preventing sensory neurons from sending pain signals to the brain. Information is transmitted along nerves by the movement of sodium ions down a carefully maintained electrochemical gradient. Local anaesthetics cut off sodium channels, preventing the ions from travelling through the membrane and stopping electrical signals travelling along the nerve.

Local anaesthesia isn't specific to pain nerves, so it will also stop information passing from the brain to the muscles, causing temporary paralysis. General anaesthetics, meanwhile, are inhaled and injected medications that act on the central nervous system to induce a temporary coma, causing unconsciousness, muscle relaxation, pain relief and amnesia.

It's not known for sure how general anaesthetics 'shut down' the brain, but there are several proposed mechanisms. Many general anaesthetics dissolve in fats and are thought to interfere with the lipid membrane that surrounds nerve cells in the brain. They disrupt neurotransmitter receptors, altering transmission of the chemical signals that let nerve cells communicate with one another.

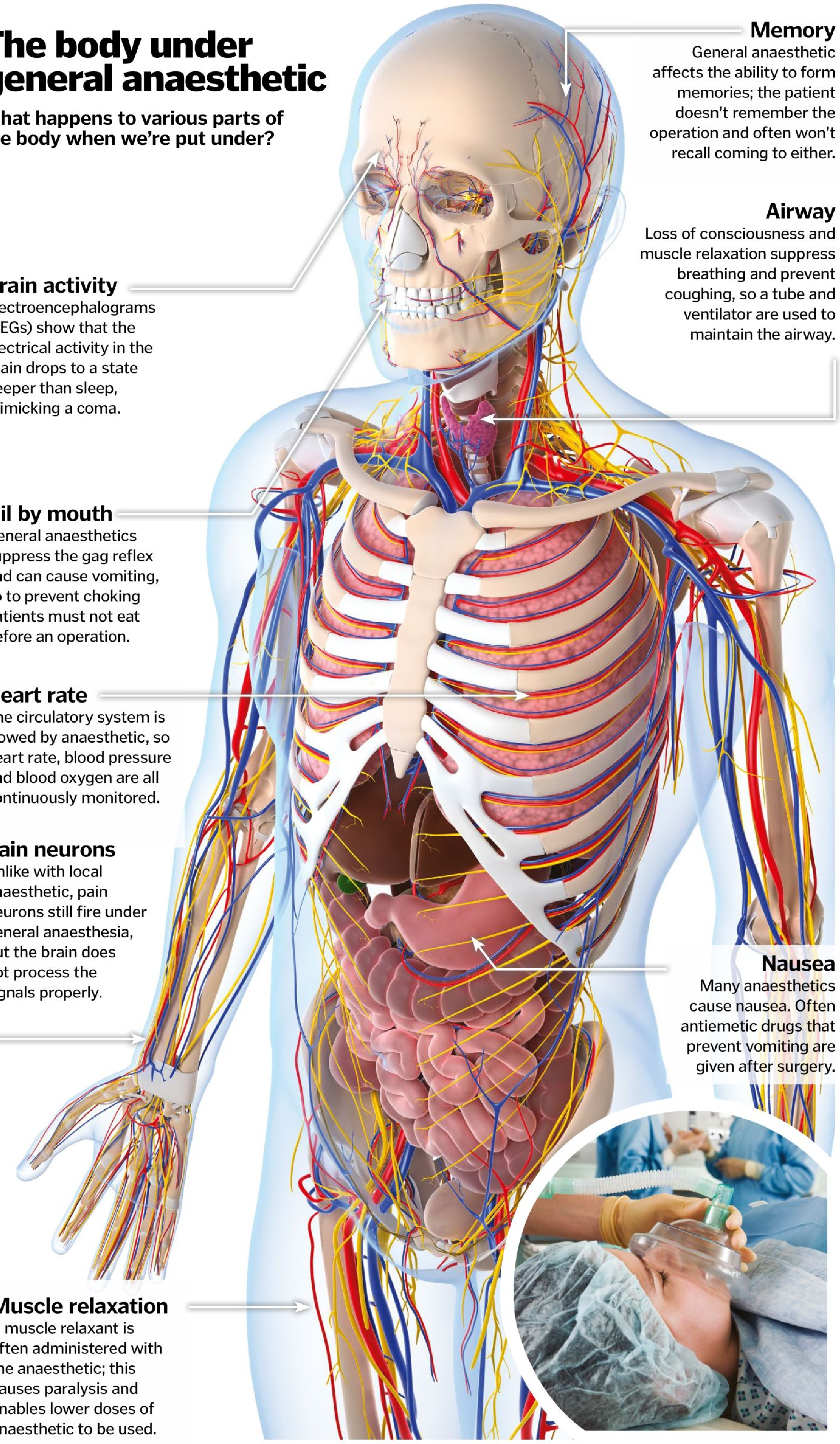
> *"Local anaesthetics provide a short-term blockade of nerve transmission"*

Comfortably numb

If large areas need to be anaesthetised while the patient is still awake, local anaesthetics can be injected around bundles of nerves. By preventing transmission through a section of a large nerve, the signals from all of the smaller nerves that feed into it can't reach the brain. For example, injecting anaesthetic around the maxillary nerve will not only generate numbness in the roof of the mouth and all of the teeth on that side, but will stop nerve transmission from the nose and sinuses too. Local anaesthetics can also be injected into the epidural space in the spinal canal. This prevents nerve transmission through the spinal roots, blocking the transmission of information to the brain. The epidural procedure is often used to mollify pain during childbirth.

The body under general anaesthetic

What happens to various parts of the body when we're put under?



Memory
General anaesthetic affects the ability to form memories; the patient doesn't remember the operation and often won't recall coming to either.

Airway
Loss of consciousness and muscle relaxation suppress breathing and prevent coughing, so a tube and ventilator are used to maintain the airway.

Brain activity
Electroencephalograms (EEGs) show that the electrical activity in the brain drops to a state deeper than sleep, mimicking a coma.

Nil by mouth
General anaesthetics suppress the gag reflex and can cause vomiting, so to prevent choking patients must not eat before an operation.

Heart rate
The circulatory system is slowed by anaesthetic, so heart rate, blood pressure and blood oxygen are all continuously monitored.

Pain neurons
Unlike with local anaesthetic, pain neurons still fire under general anaesthesia, but the brain does not process the signals properly.

Nausea
Many anaesthetics cause nausea. Often antiemetic drugs that prevent vomiting are given after surgery.

Muscle relaxation
A muscle relaxant is often administered with the anaesthetic; this causes paralysis and enables lower doses of anaesthetic to be used.

© Getty

The science behind food

Take a look at the chemistry that goes on in the kitchen when we cook our food

Some of the most interesting kitchen chemistry can be observed when baking. Taking four basic ingredients – flour, fat, sugar and eggs – and subtly altering their cooking chemistry can transform them into airy cakes, chewy cookies or flaky pastries.

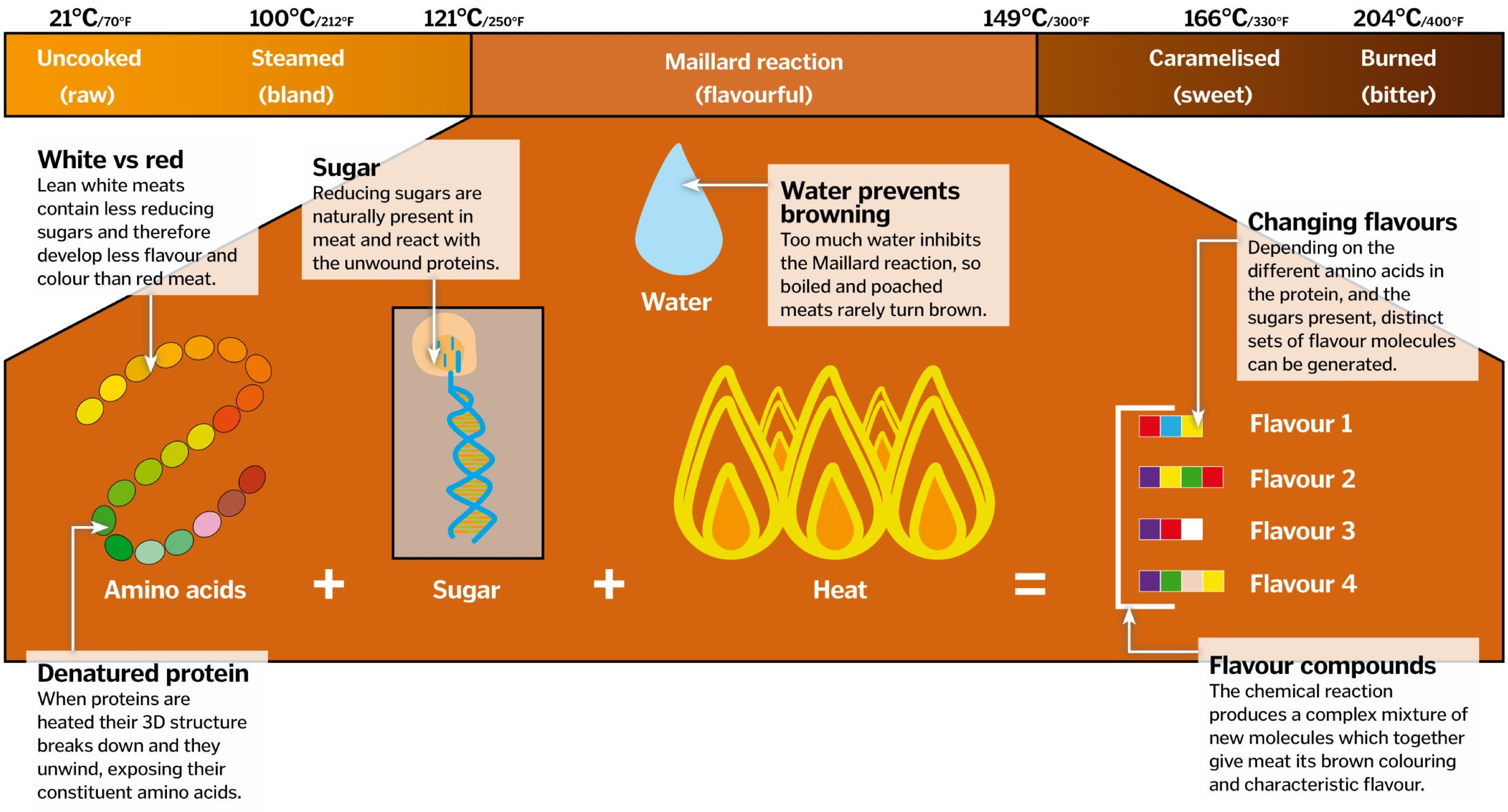
Leavening, or raising, agents introduce bubbles of air. As the air bubbles are heated, the gas that they contain expands, causing cakes, breads and soufflés to rise. These air bubbles can be made in one of two ways. Chemical raising agents, like baking powder and bicarbonate of soda, react with water to form carbon dioxide gas. This reaction occurs very rapidly and the quantity of raising agent must be carefully adjusted – too much and the bubbles will become large and burst, too little and the density of the cake mixture will prevent any bubble formation at all.

For a slower rise with added flavour, baker's yeast (Saccharomyces cerevisiae) is often used. Yeast is a single-celled organism of the fungi family. At first, the yeast respires aerobically – using oxygen – creating bubbles of carbon dioxide. When the oxygen runs out, the yeast begins to make ethanol by fermentation, much like in brewing beer, but any alcohol formed in the bread dough evaporates in the oven.

Making bubbles is one thing, but getting them to remain intact requires more clever chemistry. Bread is most often made from wheat flour, which contains starch granules surrounded by two important proteins: glutenin and gliadin. When mixed with water and kneaded, the glutenin cross-links to form networks with gliadin, making a new stretchy

Why cooked meat tastes better than raw

The brown colour of seared meat, toasted bread and roasted coffee beans is down to a chemical process called the Maillard reaction. When foods are heated, amino acids (the building blocks of protein) react with sugars to create hundreds of flavour compounds. Depending on the types and quantities of the various amino acids in the food, different combinations of flavours will be produced, as this diagram shows…



White vs red
Lean white meats contain less reducing sugars and therefore develop less flavour and colour than red meat.

Sugar
Reducing sugars are naturally present in meat and react with the unwound proteins.

Water prevents browning
Too much water inhibits the Maillard reaction, so boiled and poached meats rarely turn brown.

Changing flavours
Depending on the different amino acids in the protein, and the sugars present, distinct sets of flavour molecules can be generated.

Denatured protein
When proteins are heated their 3D structure breaks down and they unwind, exposing their constituent amino acids.

Flavour compounds
The chemical reaction produces a complex mixture of new molecules which together give meat its brown colouring and characteristic flavour.

protein: gluten. Gluten is a 'super-protein', or protein complex, which behaves much like elastic, forming stretchy bridges that hold the starch molecules together. The key to light, fluffy bread lies in creating lots of tiny elastic bubbles; the more the dough is kneaded and stretched, the stronger the gluten network becomes. Eggs act in a similar way to the gluten in flour, providing a protein-binding agent that supports air bubbles and holds cakes together.

Unlike bread, pastries need to be 'short' and crumbly, so bakers try to minimise gluten production, which would lead to a rubbery texture. This is done by first rubbing butter into the flour, coating the starch molecules with a layer of fat, which helps prevent glutenin and gliadin from coming into contact with water.

The texture of baked goods can also be altered using sugar. When sugar is beaten with butter, the sharp edges of the sugar crystals allow tiny air bubbles to form – turning the mixture a pale, creamy yellow colour. These bubbles expand in the same way as the ones created by raising agents, contributing to the light texture of cakes. For the denser consistency of cookies, melted fats and oils are often used because the tendency for bubbles to form next to the sugar crystals is reduced.

> *"Experimenting with the type of sugar used in a recipe will alter the final moisture content, and the texture"*

Sugar also draws in moisture from the air, which can have a significant effect on the water content of baked goods. Brown sugar attracts more water than white, and finely ground sugars attract more water than the granulated variety. Experimenting with the type of sugar used in a recipe will alter the final moisture content, and therefore the texture.

Chemistry isn't just limited to baking though. Chemical reactions define the taste of meat – which is around 70 per cent water, with the remainder being mostly protein and fat. Depending on the cut, meat contains a variable amount of collagen – a fibrous protein in the skin, tendons and connective tissue. The higher the collagen content, the tougher the meat is.

More expensive cuts and meat from younger animals contain little collagen and can be cooked rapidly. The muscle protein myosin denatures (breaks downs) at low temperatures – ie 50 degrees Celsius (120 degrees Fahrenheit) – and begins to form cross-links, lending some support to the structure of meat. At this stage, water molecules between the proteins start to leak out, but the meat remains juicy and tender. At 60 degrees Celsius (140 degrees Fahrenheit) the red pigment in muscle – myoglobin – denatures to form a hemichrome that gives cooked red meat its brown-grey colour.

Further heating causes the collagen to shrink and contract, forcing water out and turning the meat from juicy and tender to chewy and dry. If the temperature is raised further – to, say, 70 degrees Celsius – the meat continues to toughen, but the collagen itself dissolves to form gelatine. Although the fibres of meat are more brittle, the gelatine acts as a lubricant, giving slow-cooked meat its soft texture.

Heat isn't the only way to break down collagen, and meat can be physically or chemically tenderised. Marinades use common culinary chemicals to interfere with the bonds between collagen strands – these range from acids like lemon juice to enzymes like bromelain.

Another great example of kitchen chemistry is the emulsion process. Oil and water don't mix, but to make sauces like mayonnaise and béchamel a cook needs a way to bring them together. When oil and water are combined, the oil floats on top, forming an interface with the water that has high surface tension. In order to break this tension, mechanical shearing can be used – by shaking the container the oil breaks down into smaller and smaller bubbles, which disperse into the water. However, this is only a temporary emulsion, and after a while the oil and water will separate.

Mayonnaise contains watery egg yolks and fatty butter, which must mix to form a smooth, white paste in a permanent emulsion. Egg yolks contain an emulsifier called lecithin, which dissolves in both fat and water, essentially forming bridges between the yolk and the butter and holding the mayonnaise emulsion in a stable structure. Flour can be used in a similar way in white sauces like béchamel; the fine powder helps to bind the butter to the liquid.

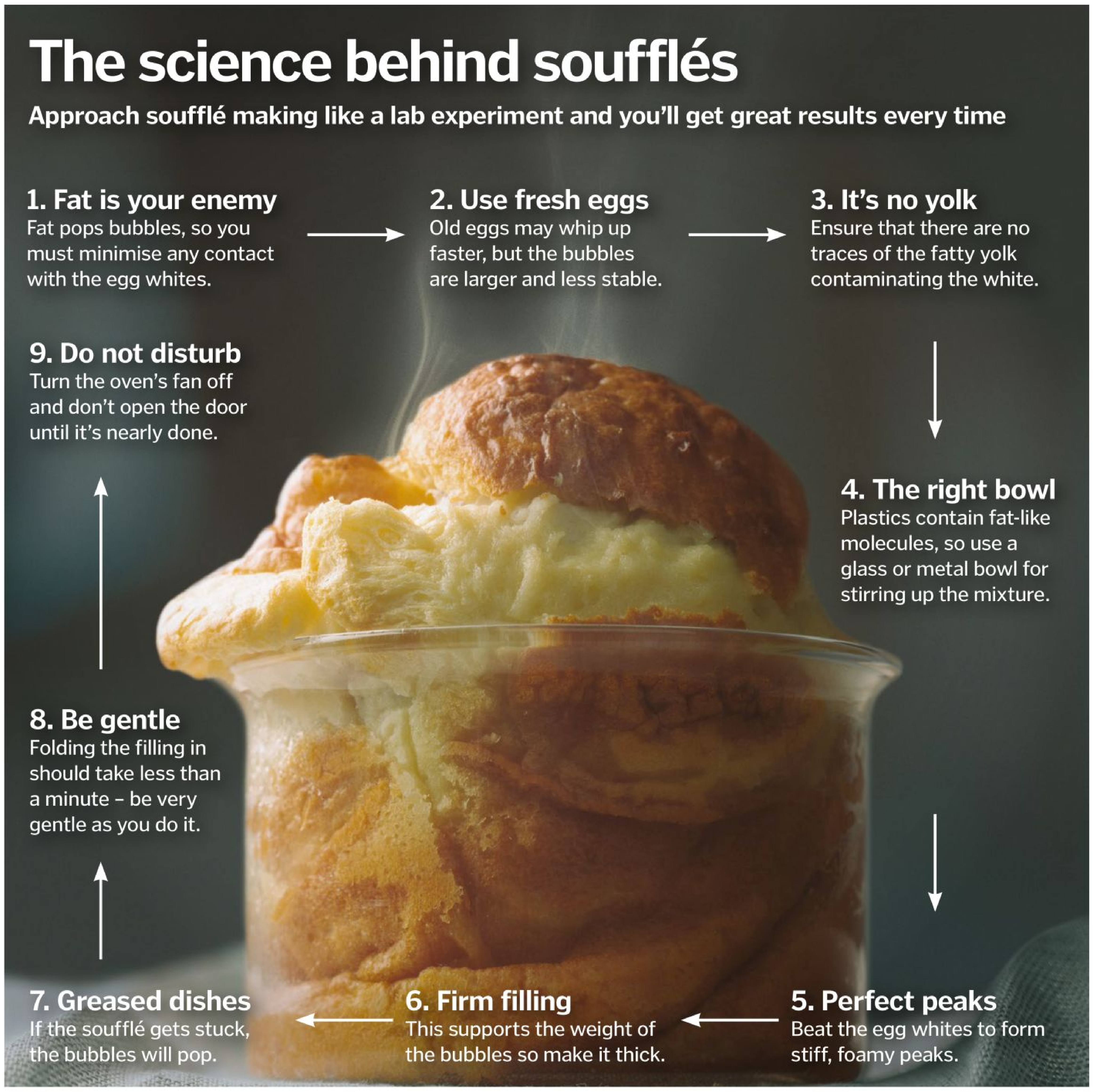
The flavour of food is determined by its combination of volatile components that get into the air and interact with sensory neurons in the nose. Each food may have hundreds of these molecules, but scientists studying flavour combinations have seen that if one of them matches, foods are likely to go together. The technique is being used to predict unlikely food partners.

Molecular gastronomy takes the science of cooking to the next level. Looking at food from a purely physical and chemical perspective, a host of chefs and scientists are coming together to identify new flavour combinations and cooking techniques based on science. Using liquid nitrogen, syringes, centrifuges and ultrasound machines, we are starting to reinvent the way we cook. As the founding father of this scientific discipline, Nicholas Kurti, said: "It's a sad reflection on civilisation that while we can and do measure the temperature in the atmosphere of Venus we do not know what goes on inside our soufflés."

> "Marinades use common culinary chemicals to interfere with the bonds between collagen strands"

The science behind soufflés

Approach soufflé making like a lab experiment and you'll get great results every time



1. Fat is your enemy
Fat pops bubbles, so you must minimise any contact with the egg whites.

2. Use fresh eggs
Old eggs may whip up faster, but the bubbles are larger and less stable.

3. It's no yolk
Ensure that there are no traces of the fatty yolk contaminating the white.

4. The right bowl
Plastics contain fat-like molecules, so use a glass or metal bowl for stirring up the mixture.

5. Perfect peaks
Beat the egg whites to form stiff, foamy peaks.

6. Firm filling
This supports the weight of the bubbles so make it thick.

7. Greased dishes
If the soufflé gets stuck, the bubbles will pop.

8. Be gentle
Folding the filling in should take less than a minute – be very gentle as you do it.

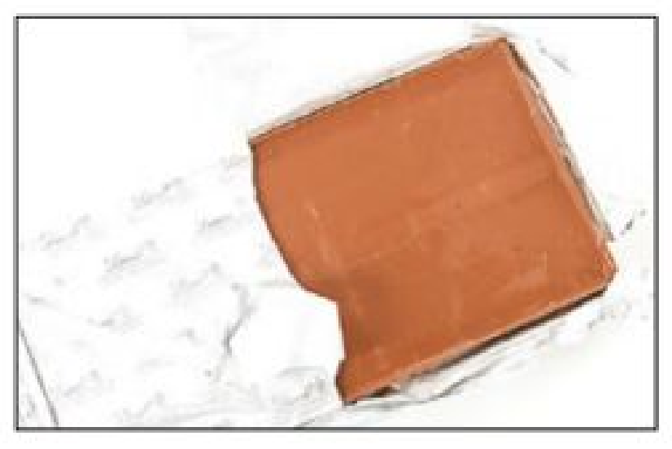
9. Do not disturb
Turn the oven's fan off and don't open the door until it's nearly done.

Strange flavour combinations

Some seemingly odd food pairings are surprisingly good, others are just plain disgusting – but why?

Chocolate and salt

Salt actually helps the cells on your tongue to sense the presence of sugar, so it makes chocolate taste even sweeter.


+

= YUM

Peanut butter and apple

Peanut butter makes up for what an apple lacks in salt and fat, while the apple cuts through the spread's richness and stickiness.

+

= YUM

Citrus fruit and milk

The acid found in citrus fruit causes milk to separate and curdle – essentially the first step in making cheese. Not appetising.

+

= YUCK

Chilli powder and fruit

The compound capsaicin present in chilli has two effects: it enhances our sense of smell and also heightens our perception of sweetness.

+

= YUM

Coffee and olives

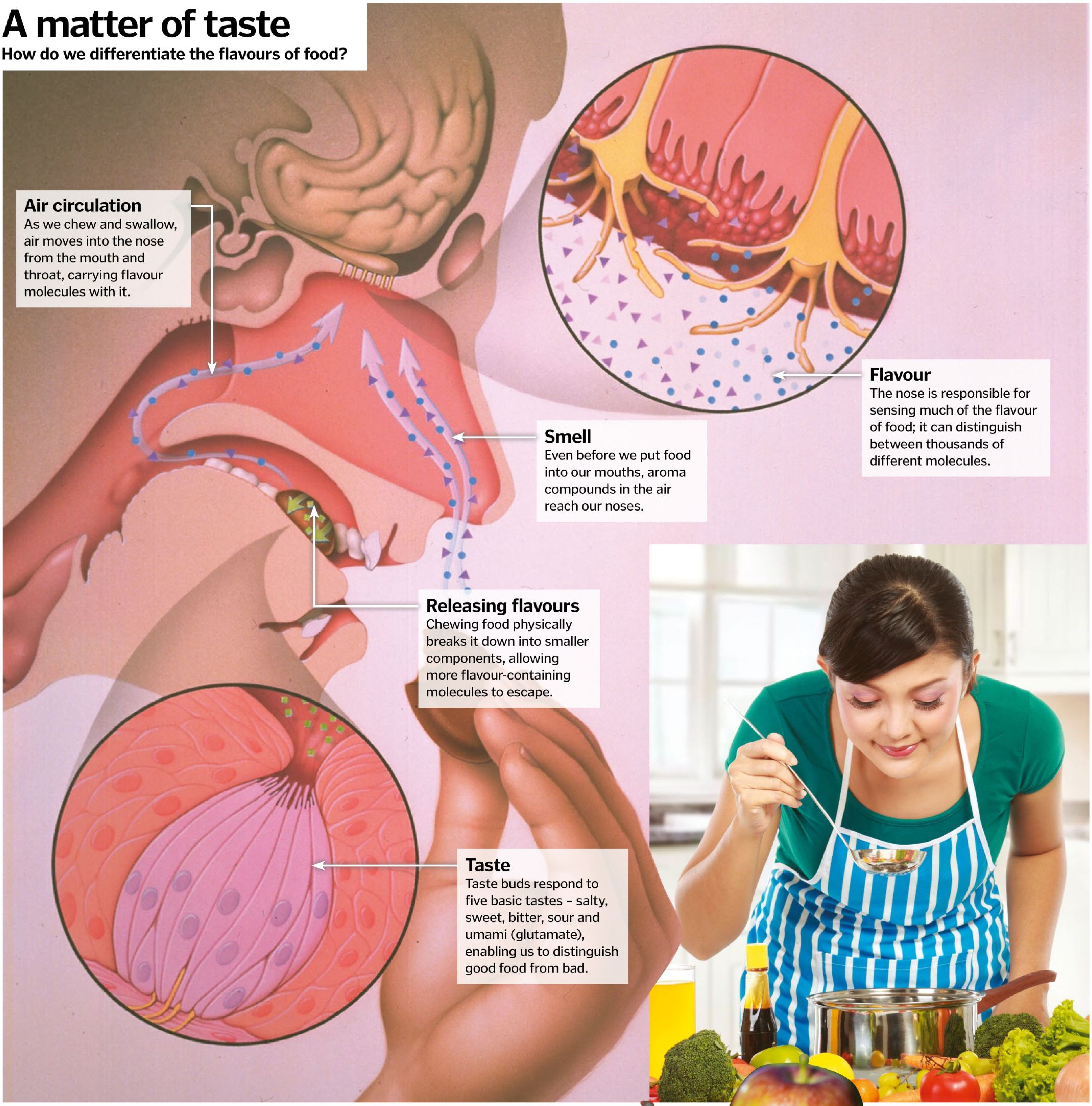
We evolved to associate bitterness with poison, so combining too many bitter flavours is often unpleasant.

+

= YUCK

A matter of taste

How do we differentiate the flavours of food?



Air circulation
As we chew and swallow, air moves into the nose from the mouth and throat, carrying flavour molecules with it.

Smell
Even before we put food into our mouths, aroma compounds in the air reach our noses.

Flavour
The nose is responsible for sensing much of the flavour of food; it can distinguish between thousands of different molecules.

Releasing flavours
Chewing food physically breaks it down into smaller components, allowing more flavour-containing molecules to escape.

Taste
Taste buds respond to five basic tastes – salty, sweet, bitter, sour and umami (glutamate), enabling us to distinguish good food from bad.

Can food make us happy?

People often report cravings for particular foods, and that eating certain meals makes them happy. As a species, we evolved to make eating a pleasant experience, encouraging us to seek out high-calorie food to sustain ourselves when food was scarce.

The human brain has developed reward pathways associated with eating fat and sugar, which release mood-enhancing neurotransmitters, like dopamine and endorphins. Probably the most-studied example is chocolate, which contains phenylethylamine and this affects the body's opioid production.

Comfort food, on the other hand, works more psychologically, and the pleasant feelings that it induces are often linked to sight, smell and taste, which can trigger a sense of nostalgia.

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Cosmetic chemistry

Lotions and potions are packed with chemical science, but do they live up to the hype?

Mattifying makeup

Mattifying makeup products attempt to minimise shine by including ingredients that absorb oil and water. Clays are made from oxygen or oxygen and hydrogen (hydroxyl groups) and arranged into crystals with four or eight sides. At the centre of each is an atom of silicon or aluminium. These structures form sheets, and it's between these sheets that oil and water become trapped. Mattifying agents can be found in a variety of products, including powders, foundations, lotions, balms, gels and sprays.

Silicone elastomers are a synthetic alternative. They are made from chains of silicone, carbon, hydrogen and oxygen strung together to form branching webs. These expand when liquids are added, helping to lock moisture away.

Anti-wrinkle creams

Proteins are the major building blocks of the human body and collagen and elastin are two critical types found in skin. They form a web-like scaffold that holds skin cells in place; collagen provides structure and elastin provides springiness. However, as we get older, we produce less and less of both, and skin starts to lose its firm, flexible texture.

One solution employed by cosmetics giants is to add fragments of protein to their creams. This helps to smooth out wrinkles, but probably not in the way you were expecting. Rather than repairing the collagen and elastin scaffolding, the fragments work by improving skin texture from the outside. They go on damp and flexible, and as they dry out they tighten up. This tugs on the skin beneath, temporarily smoothing out the wrinkles.

> "Exfoliating washes contain fragments of sugar, nut shells or plastic that act as abrasives"

Whitening toothpaste

Whitening toothpastes work like a rough polish, using abrasive grains to scrape away the film of bacteria and pigments that continually builds on the surface of the enamel. However, they can't change the colour of the teeth beneath. For teeth whiter than a natural shade, chemical bleaching is the only option. Whitening strips contain carbamide peroxide, which breaks down chromophores, the parts of molecules responsible for their colour.

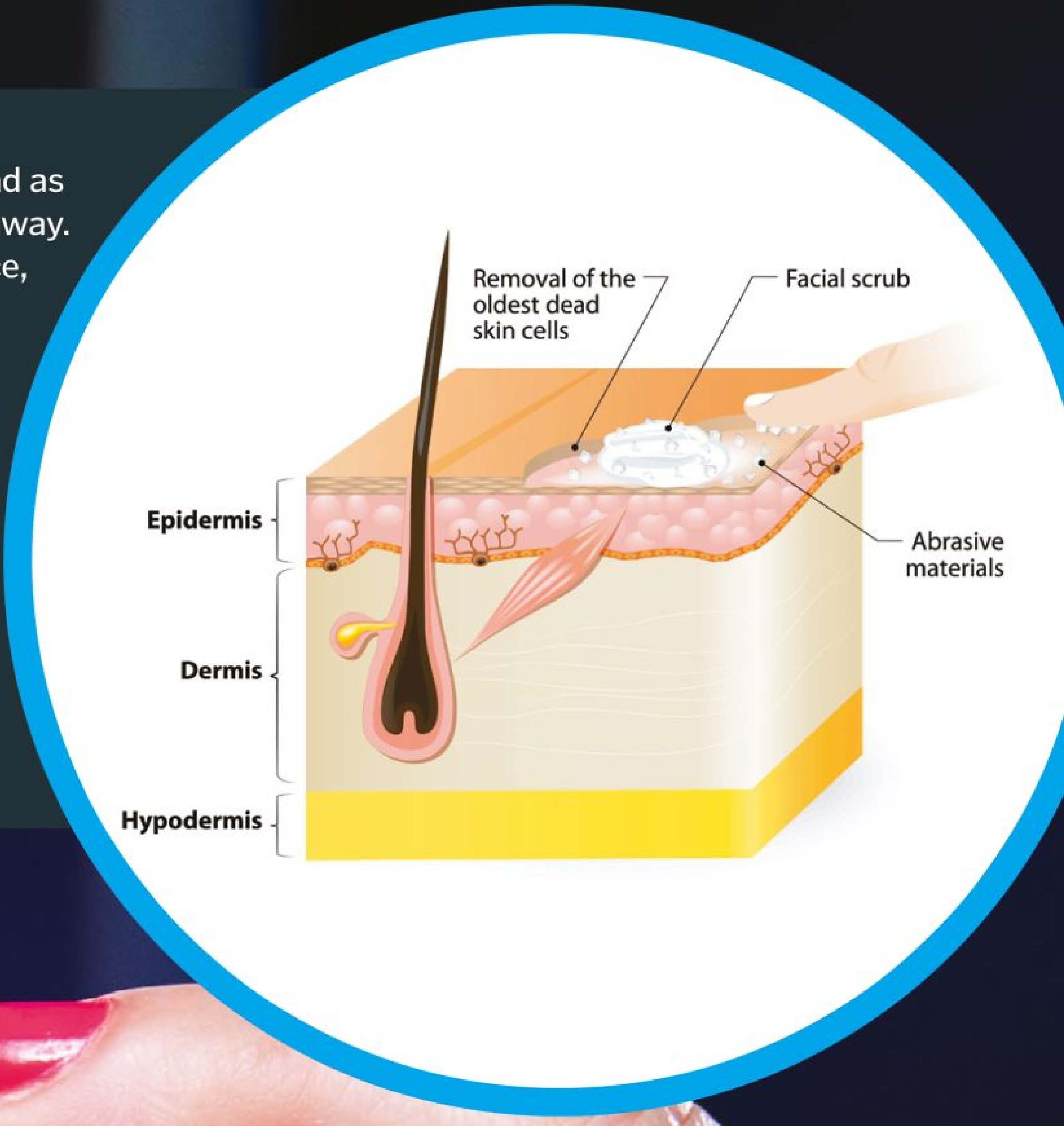
Waterproof mascara

Mascara colours the eyelashes using pigments like carbon black (made by the incomplete burning of petrochemicals) and iron oxides (which come in varying shades of red and brown). For ease of application, they are suspended in oils, waxes and water, forming a paste that can be spread onto the lashes with a brush. These carriers include beeswax, shellac (a type of resin made by lac bugs), lanolin (from sheep) and paraffin.

Waterproof mascaras tend to contain more waxes and oils than their water soluble counterparts, helping them to resist moisture and stay on the lashes longer. But, because they've been designed not to dissolve in water, they can be a challenge to wash off. Oily makeup removers help to dissolve the waxy carriers that stick the pigments to the lashes. The mascaras themselves sometimes contain lubricants, like glyceryl stearate, which help the mixture to stay slippy.

Exfoliators

The skin is in a constant state of renewal, and as new skin cells are made, the old ones flake away. Exfoliators help to rub these from the surface, making the skin look smoother and brighter. The textured surface of a washcloth is enough to gently scrub away some of the surface cells, but many treatments offer a deeper cleanse. Exfoliating washes contain tiny fragments of sugar, crushed nut shells or plastic that act as abrasives. Chemical peels use acids (commonly salicylic or lactic acid) to create a controlled burn, and microdermabrasion uses a rough rotating brush to scrape away even more of the skin's surface.



Shimmery shadows

The glitter and sheen in eyeshadows and highlighters is most commonly mica or bismuth oxychloride. Mica bends the light as it hits, while bismuth oxychloride has a pearlescent appearance. If mica is combined with titanium dioxide the way it reflects light changes, creating iridescent shades.

Makeup primers

Primers contain lots of ingredients that aim to keep makeup looking fresh all day. Silicones help to absorb moisture and oils, while waxes and polymers form a bridge that sticks cosmetics to the skin. Spherical silicone molecules coated with titanium dioxide help to diffuse light, evening out blemishes and creating an 'airbrushed' look.

Cosmetic myths

1 Bypassing the barrier

Creams might contain vitamins, proteins or even DNA and be accompanied by claims that the molecules will repair the tissue underneath. But skin is a barrier; not everything can get through.

2 Stretch mark miracles

Hydrated skin hides blemishes better than dry skin, but stretch marks are scars, so no amount of moisturiser is truly going to remove them.

3 Hot water opens pores

Pores don't open and close, and you can't do anything to change their size. However, warm water can help to loosen anything that might be stuck inside your pores.

4 'Clinically proven'

Be wary of cosmetic science claims. Studies can be small or involve experiments using raw ingredients in test tubes, not the actual product on real people.

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Elements, mixtures and compounds

What are the differences between these configurations of atoms?

All matter is made up of atoms – these are tiny particles that cannot be seen through the lense of a conventional microscope.

Atoms make up the table of elements, and all elements are made up of the same parts: protons, neutrons and electrons. The atoms of a particular element are all the same as each other, as they all contain the same number of protons in their nuclei.

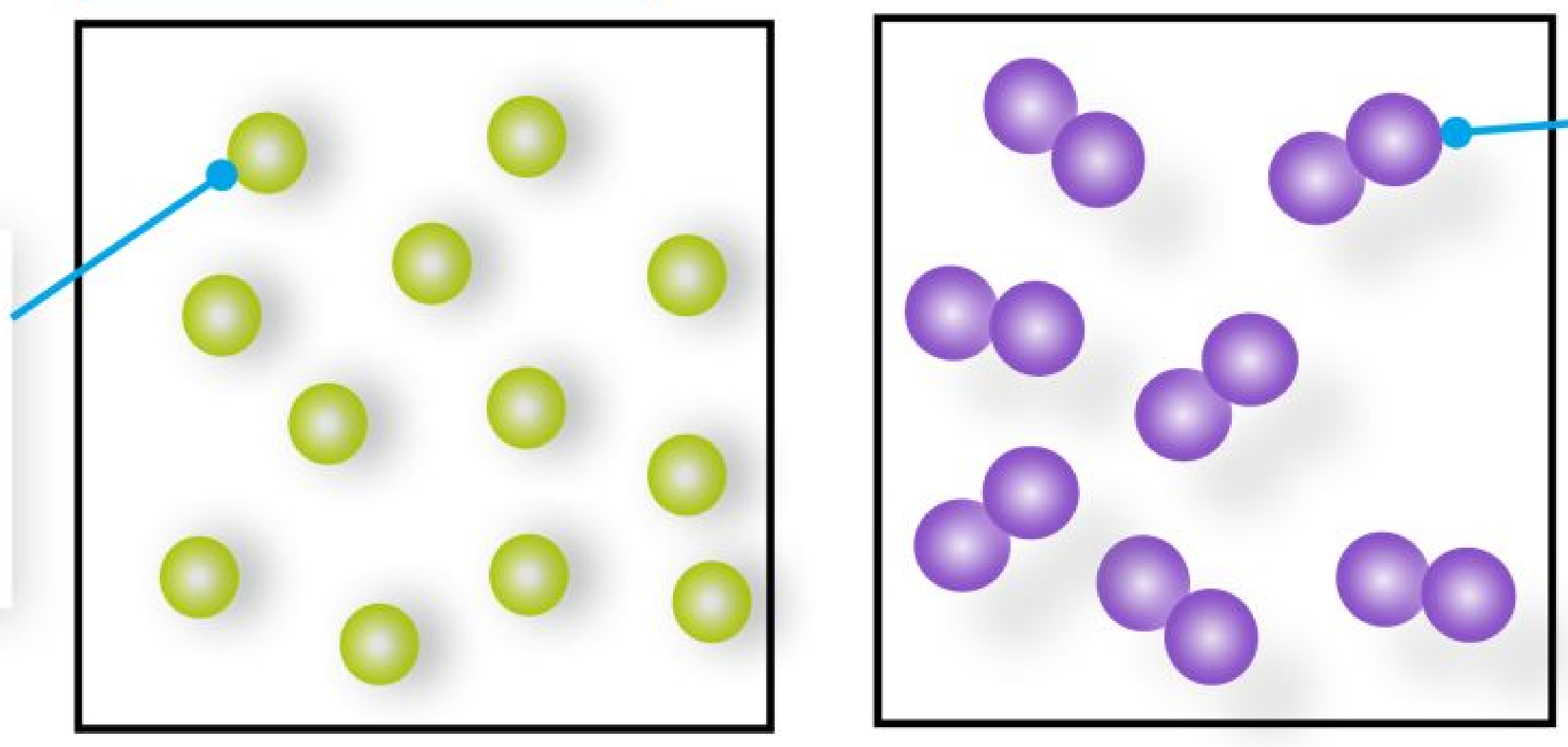
A compound contains atoms of two or more different elements, which are chemically joined together. Water is a compound that contains two hydrogen atoms and one oxygen atom.

A mixture is a substance consisting of different atoms, molecules or compounds that aren't chemically joined. Air, for example, is a mixture of nitrogen, oxygen, argon and others.

How do they differ?

A guide to how atoms make up elements, mixtures and compounds

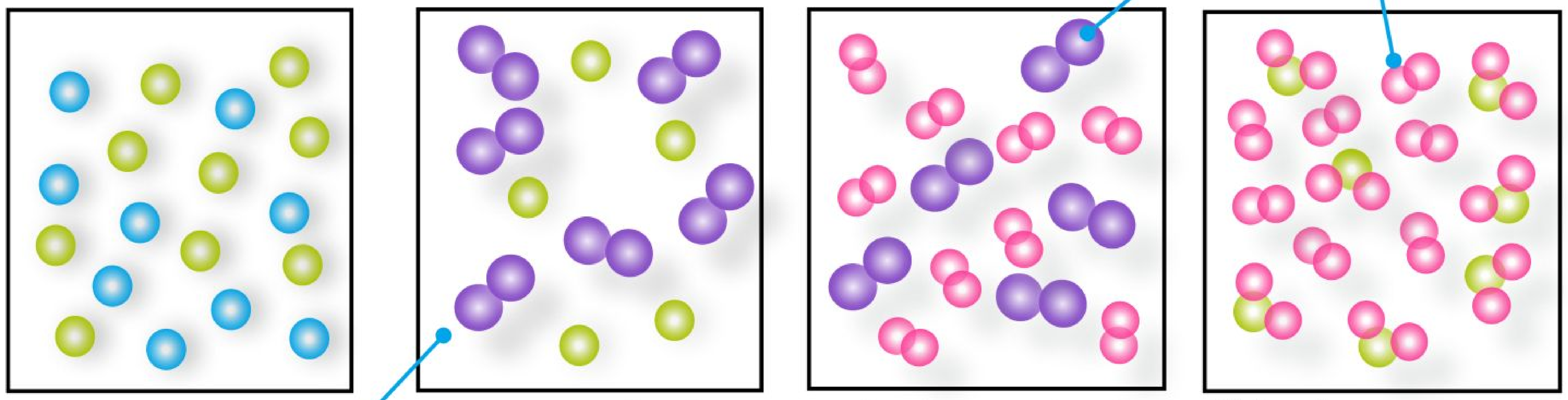
Elements



Atoms
Atoms are represented by single spheres of the same size and colour.

Molecules
Molecules are represented by two or more spheres joined together.

Mixtures



Atoms + atoms

Atoms + molecules

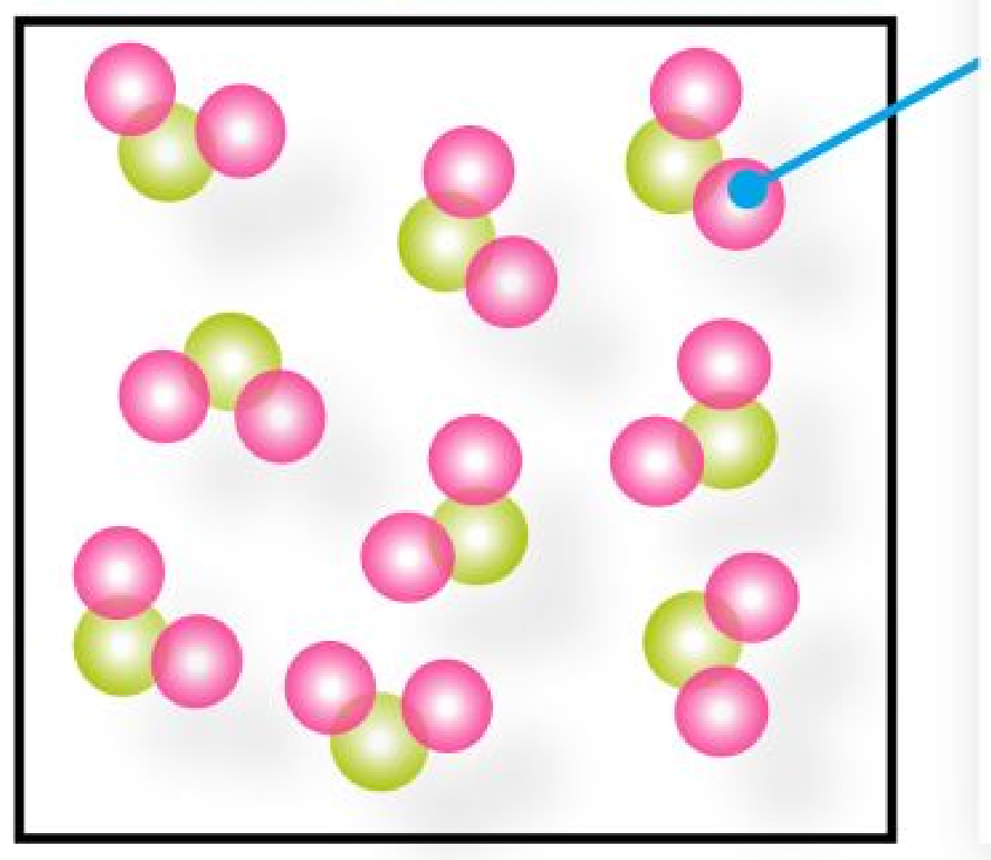
Molecules + molecules

Molecules + compounds

Molecules of elements
Molecules form when any two or more atoms join together. All compounds are molecules.

Mixtures
Mixtures can consist of individual atoms, molecules and compounds, but they're not chemically joined.

Compounds



Compounds
Compounds form when at least two different elements join together. Not all molecules are compounds, as some molecules contain only a single element.

> "Substances in mixtures are not chemically bound together"

Limescale

Discover what causes limescale and how chemical descalers can remove it

Limescale is a crusty, off-white deposit of calcium carbonate left behind by hard water, and mostly found in your kettle and boiler. Hard water contains an above average concentration of dissolved minerals, like calcium and magnesium ions. Limescale becomes an issue when hard water is heated or left to stand. When the moisture evaporates, the dissolved minerals solidify and turn to limescale, which is difficult to remove. A build-up of limescale in central heating pipes, washing machines and dishwashers can restrict water flow, making them less efficient and can even clog them up completely.

Fortunately, there are ways to remove limescale. For example, ion exchange columns contain ion exchange resin in the form of beads. As water passes through the column, the calcium and magnesium ions in the water swap places with the ions in the column, gradually removing the unwanted minerals. Citric acid, sesquicarbonate and other compounds can also be found in water-softening agents, which prevent the calcium and magnesium ions from forming limescale deposits. Acids are used in most limescale removers because they react with limescale and produce soluble metal salts that can be washed away.

Build-up
Evaporated hard water leaves behind a calcium carbonate deposit.

Limescale haven
The warm drum of a washing machine can encourage limescale.

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Heat transfer

Get the 60-second lowdown on how heat gets from A to B

Our universe is made up of matter and energy, and its particles are always in motion. You can measure this motion with a thermometer. The temperature tells you the average kinetic energy – the more the particles are moving, the higher the temperature will be.

Heat is the transfer of this energy from one place to another. If an object feels warm, it's because it is transferring energy to your body. This can happen in three ways: conduction, convection and radiation. This understanding of heat developed in the 1800s and overturned many now obsolete theories that were proposed before it.

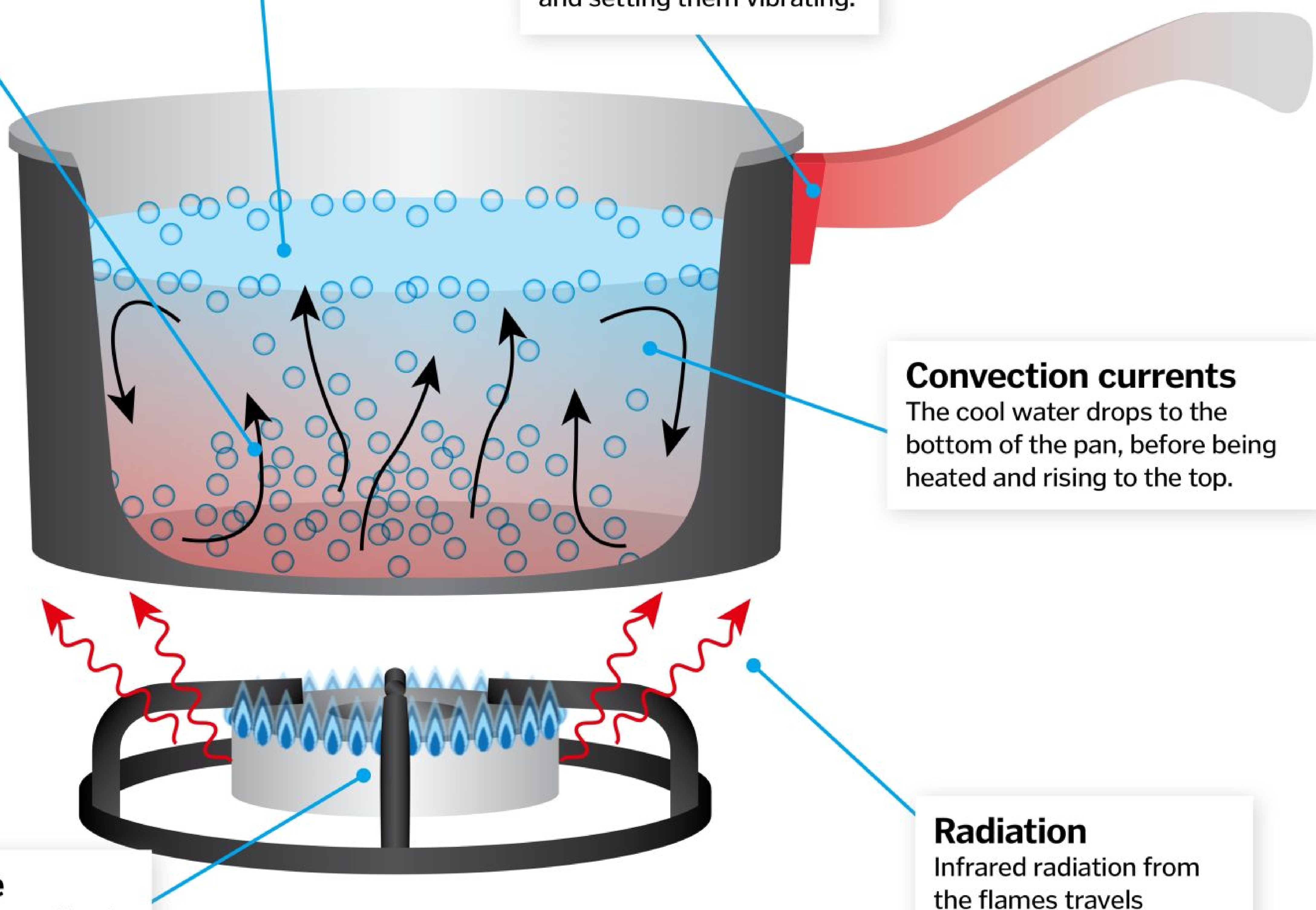
Conduction is the transfer of heat through solids by the movement of particles. Heat energy is transferred by movement, and if moving particles bash into each other, they will pass some of their energy on. Metals are good at conducting heat because they have free electrons that can move around inside, taking heat with them.

Convection happens in fluids. When liquids and gasses are heated, the particles inside them move faster. This causes the warm fluid to expand and become less dense, rising above the colder fluid. As the colder fluid is heated, it expands and rises, and as the warm fluid cools, it contracts and falls, creating convection currents.

All objects also emit infrared radiation. The higher the temperature, the more radiation is released. These electromagnetic waves can travel through a vacuum, allowing heat to be transferred even in space.

Heat transfer in action

Boiling a pan of water uses all three methods of heat transfer



Expansion
The fast-moving water molecules get further apart and the heated water becomes less dense.

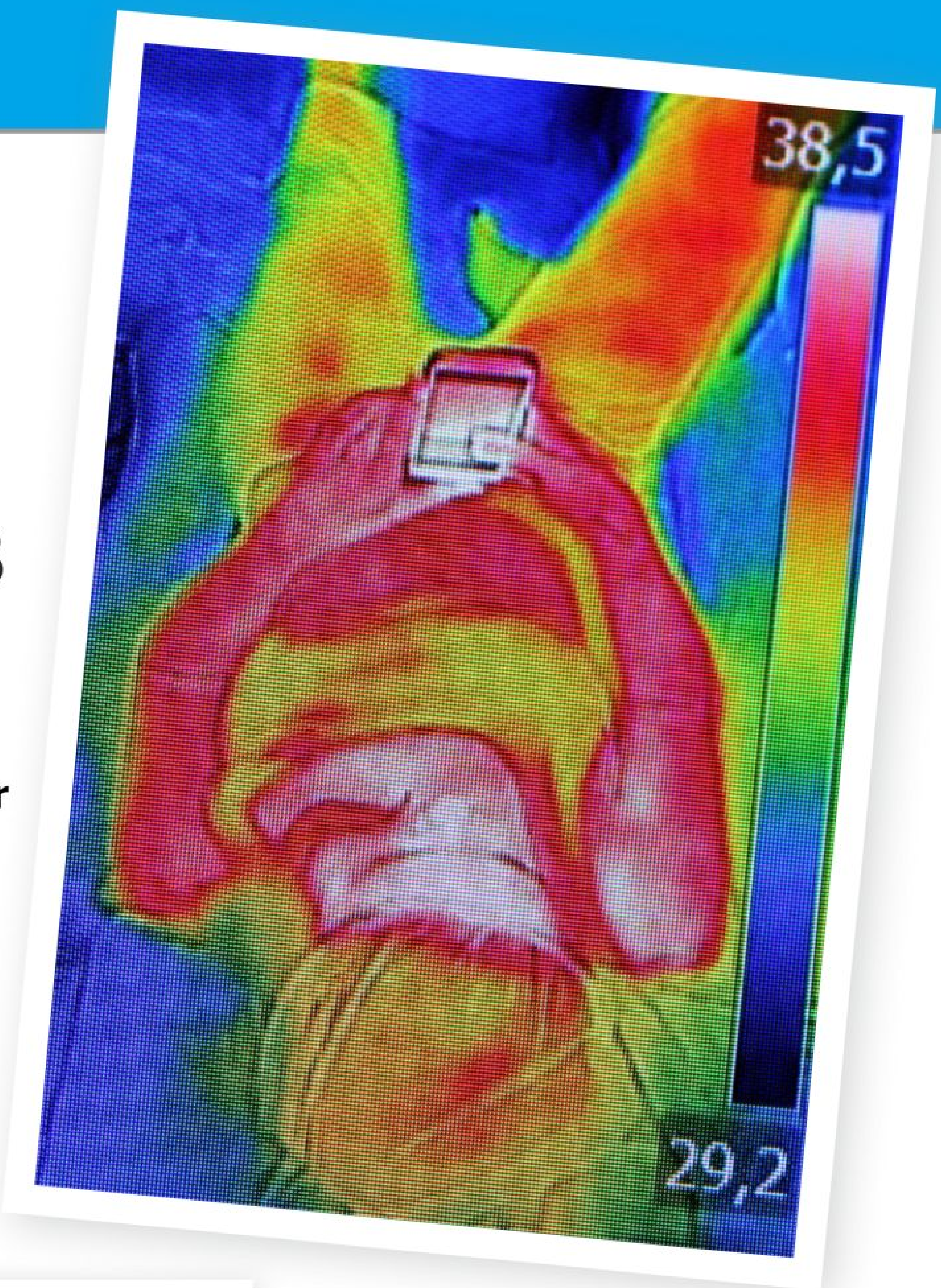
Convection
As the water at the bottom of the pan heats up, the molecules move faster.

Conduction
The free electrons in the metal pan transfer heat by bumping into molecules and setting them vibrating.

Convection currents
The cool water drops to the bottom of the pan, before being heated and rising to the top.

Heat source
The combustion reaction in the fire converts chemical energy to thermal energy.

Radiation
Infrared radiation from the flames travels through the air, colliding with the metal of the pan.



Infrared cameras reveal the thermal radiation emitted by different objects

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The first law of thermodynamics

Thermodynamics is the science of energy and work. In 1850, scientists Rudolf clausius and William Thomson, (Baron Kelvin, after whom the unit kelvin is named) stated the first law of thermodynamics, which describes energy conservation. Energy cannot be created or destroyed, but it can travel from one place to another. It can also be converted into other types of energy, for example, chemical, electrical, light and sound energy.

The first law states that the amount of energy in a system is equal to the heat transfer minus the work done. For example, in a car engine, a spark ignites petrol gas, converting chemical energy into thermal energy and causing the gas to expand inside a closed cylinder. This pushes against a piston and, as the piston moves, it turns the crankshaft. The thermal energy is converted into kinetic energy in order to move the car.

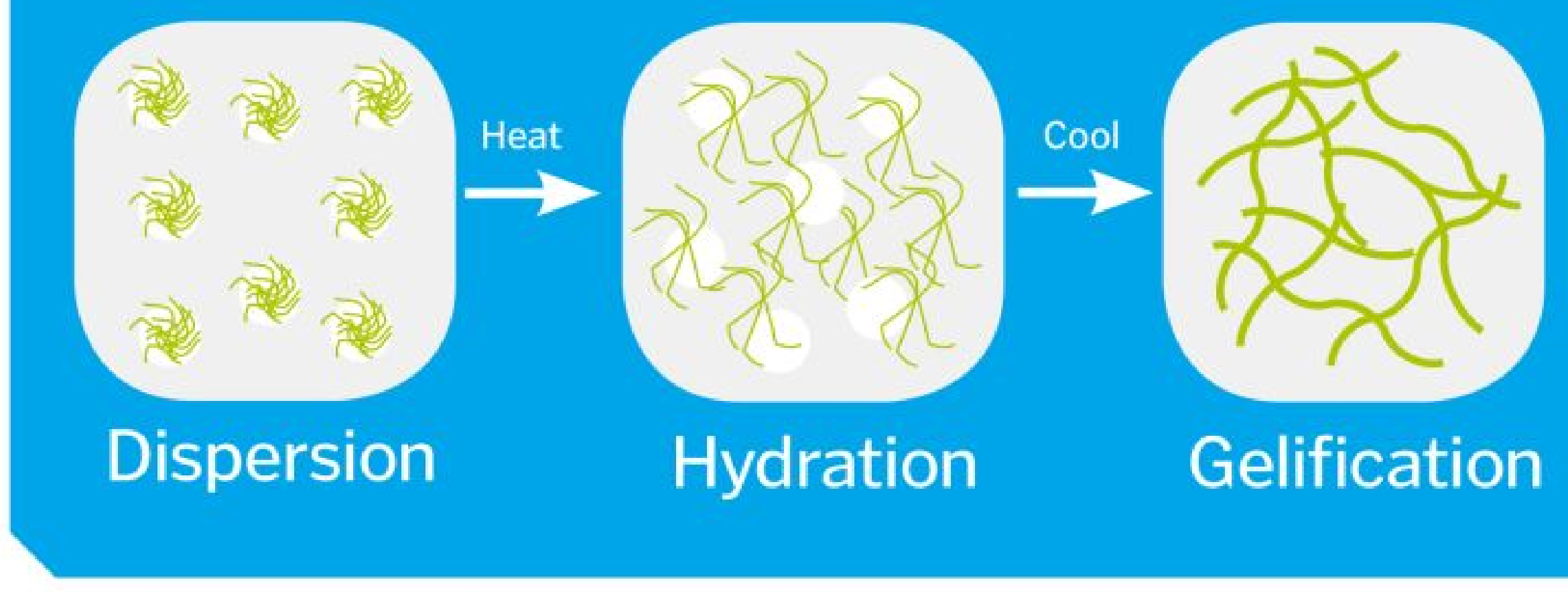
Creative culinary science

Feast your eyes on the delicious dishes created by the top chefs trained in molecular gastronomy

Foam can be used to present familiar flavours in an unfamiliar texture

Gels

When experimenting with textures, chefs are able to turn liquids into solids by adding a gelling agent called a hydrocolloid. Common hydrocolloids used in cooking include gelatine, agar-agar and sodium alginate and are made of tightly-wound coils of long protein or carbohydrate molecules. When added to liquid, the molecules evenly disperse and then heat is applied to cause them to hydrate and unfurl. As the mixture cools back down again the long strands form a crosslinked network that traps the liquid molecules and forms a solid shape. The result is a firm gel or jelly packed full of the flavour of the original liquid.



Liquid nitrogen

To introduce some drama to their food presentation, chefs can garnish their drinks and dishes with a dash of liquid nitrogen to produce a magical smoke effect.

Nitrogen is normally a harmless, odourless and tasteless gas and is present in the air we breathe, but when cooled to below -196 degrees Celsius it becomes a liquid. If it is exposed to warmer temperatures again, it quickly boils and evaporates, condensing the moisture in the surrounding air to create a dense fog.

Liquid nitrogen isn't just useful for decoration, though, as it can also be used to make delicious frozen desserts. When making ice cream, the supercooled liquid will freeze the ingredients instantly. This prevents ice crystals from forming so that the finished product is incredibly smooth and creamy.

Nitrogen must be handled with care as a liquid but is harmless as a gas

Spherification

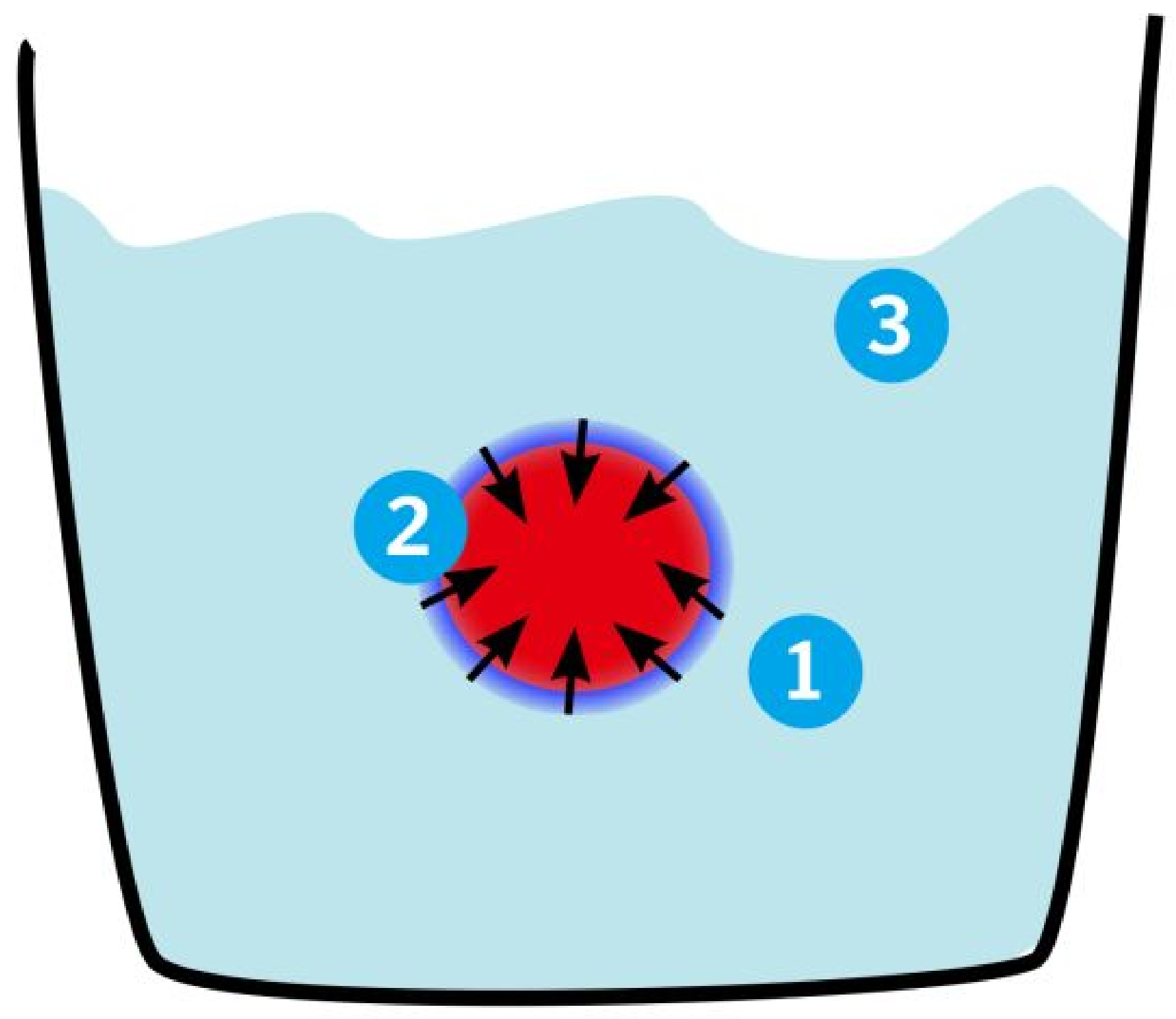
To add an explosion of flavour to a dish or cocktail, chefs can use clever chemistry to create spheres of flavoured liquid. The liquid is contained inside a thin gel membrane that when put under slight pressure in your mouth, bursts open to reveal the delicious contents within.

The spheres can be created using one of two spherification techniques. Basic spherification has the benefit of creating an extremely thin gel membrane that is almost imperceptible in your mouth, but this will not work if the liquid has a high acidity. The gel also keeps forming after the liquid is removed from the bath, so the sphere must be served immediately, before it becomes a solid gel ball.

Reverse spherification is best used for liquids with a high calcium or alcohol content, and although it creates a thicker membrane, the finished sphere is longer lasting as the gel stops forming as soon as it is removed from the bath.

Spherification can be used to create small, caviar-like balls or large domes

Basic spherification

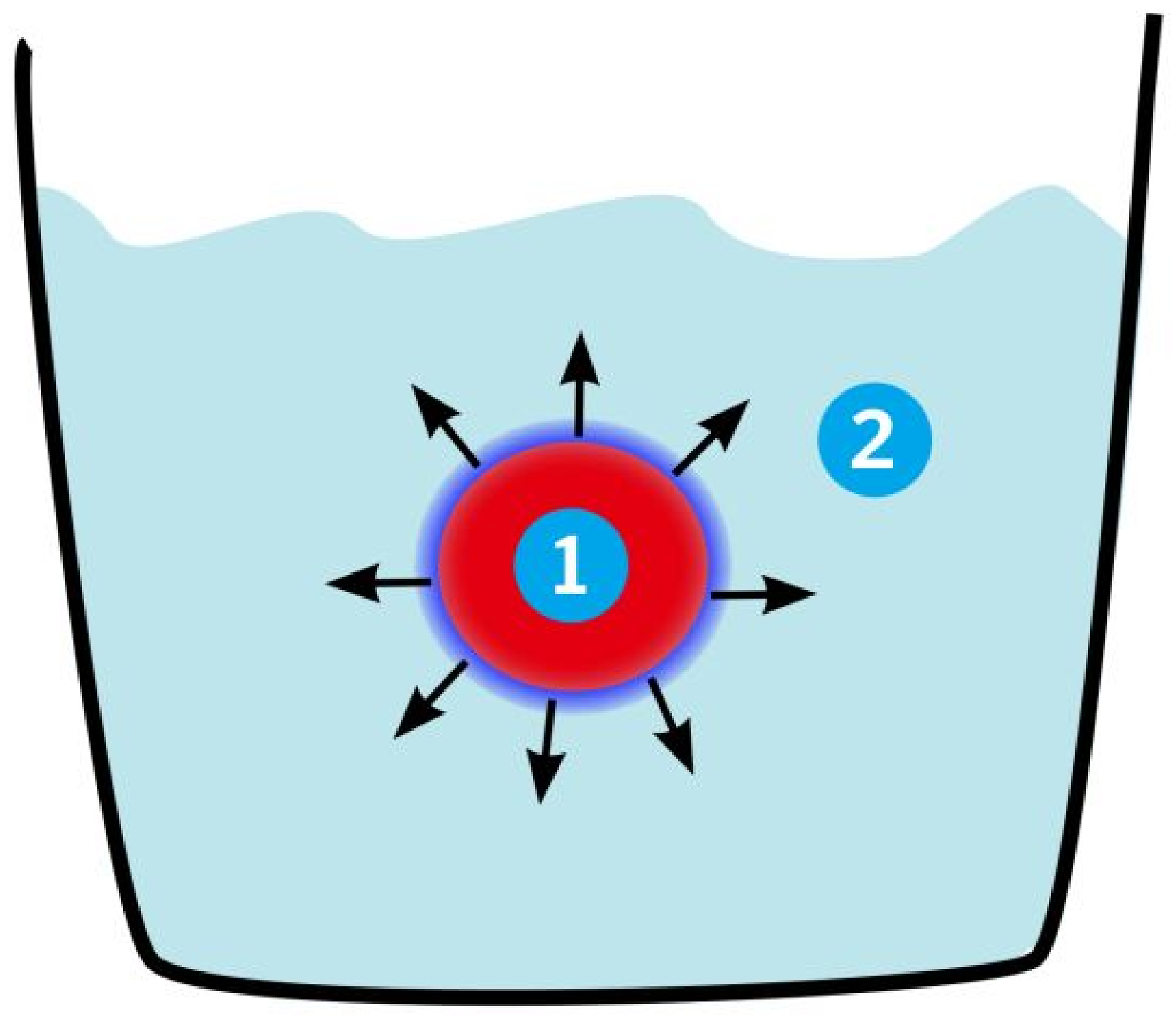


1. Sodium alginate solution
Sodium alginate is dissolved in the flavoured liquid and dropped into a bath of calcium lactate.

2. Gel coating
The calcium ions diffuse towards the centre of the droplet even after it is removed from the calcium bath.

3. Calcium lactate bath
Calcium ions displace the sodium from the alginate molecules and hold them together to form a gel.

Reverse spherification



1. Calcium lactate solution
Flavoured liquid is infused with calcium lactate and then dropped into a bath of sodium alginate.

2. Sodium alginate bath
Calcium ions diffuse from the droplet into the alginate, forming an outer gel layer until it is removed from the bath.

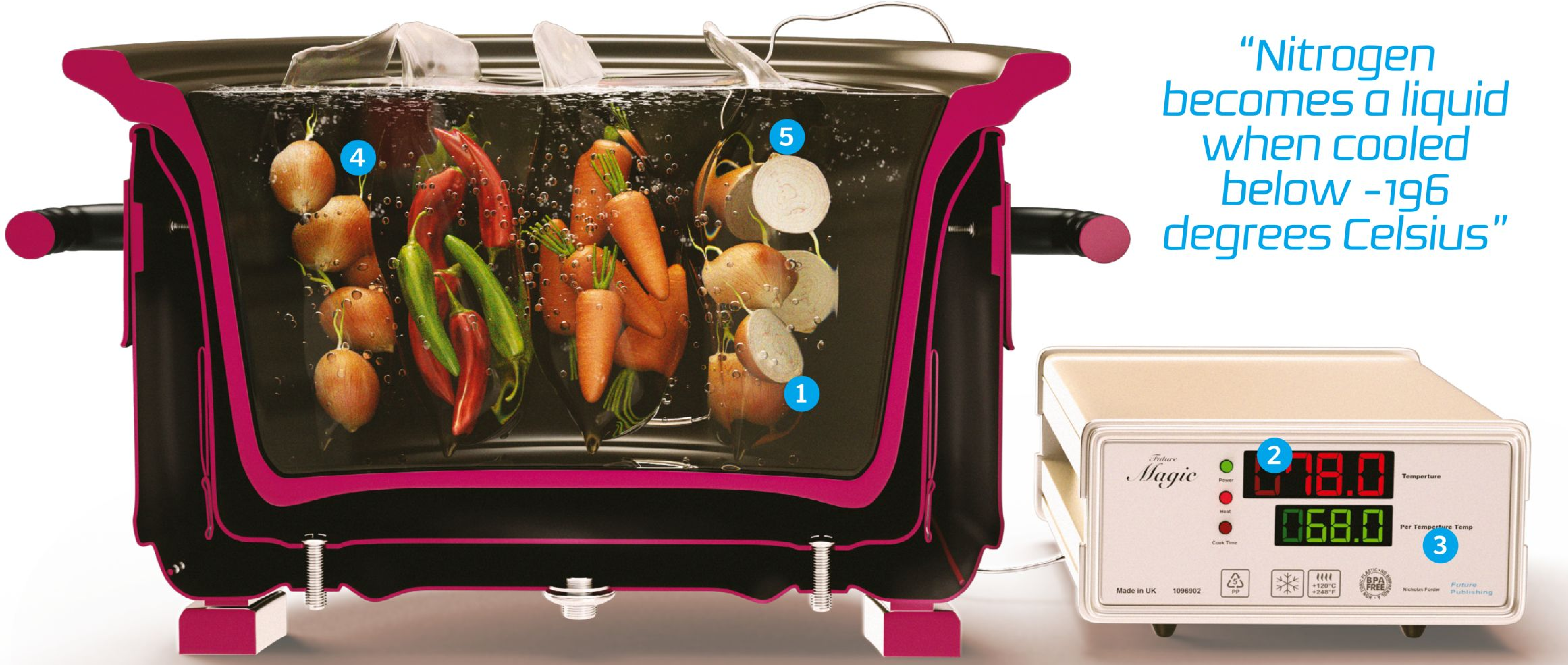
Sous vide

To ensure their food is cooked to perfection, many top chefs use a method called sous vide, which is French for 'under vacuum'. It involves sealing raw ingredients in vacuumed pouches and then placing them in a water bath heated to a precise temperature. This cooks the food evenly from edge to edge, maintaining moisture and tenderness in the centre while preventing the outsides from being overdone.

Despite the name, vacuum sealing isn't actually vital for sous vide, as temperature control is more important. However, it does have certain benefits. Sealing the food allows for more efficient heat transfer from the water and retains moisture and flavour during cooking. It also inhibits off-flavours that can occur when food is exposed to oxygen in the air. It's a process thought to date back to 1799.

Sous vide can make thick cuts of meat tender yet still medium-rare all the way through

> "Nitrogen becomes a liquid when cooled below -196 degrees Celsius"



1. Efficient cooking
Water transfers heat more efficiently than air, so food can be cooked at lower temperatures.

2. Succulent flavour
Cooking at low temperatures means the cell walls in food do not burst, providing a higher level of succulence.

3. Perfect 'doneness'
Precise temperature control ensures proteins, such as fish, chicken and eggs, are cooked to perfection.

4. Safe to eat
Cooking at exact temperatures and times ensures the food is safe to eat and determines expected shelf life.

5. Ideal texture
When cooking vegetables, low temperatures ensure they are cooked thoroughly but maintain a crisp texture.

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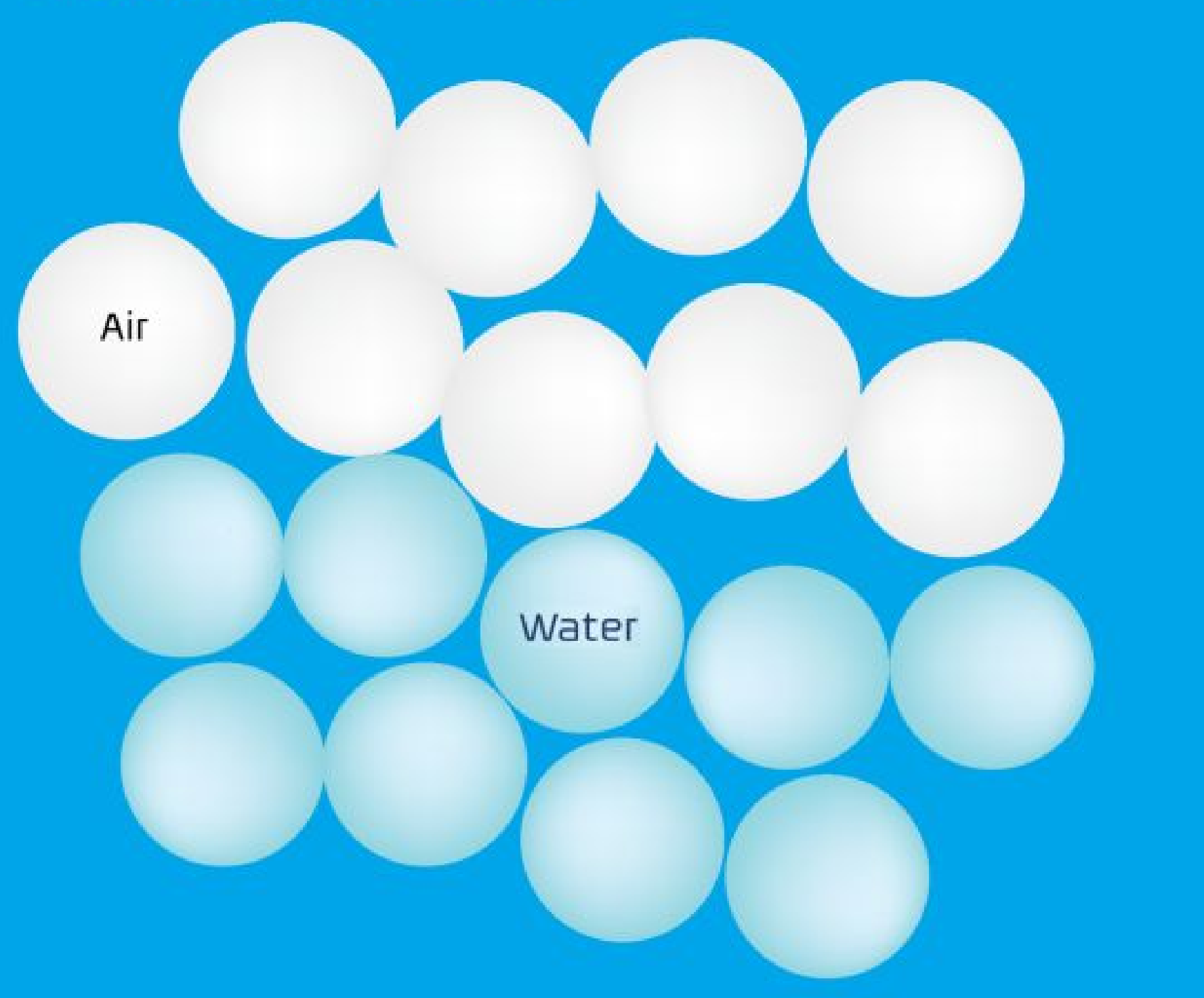
Foams

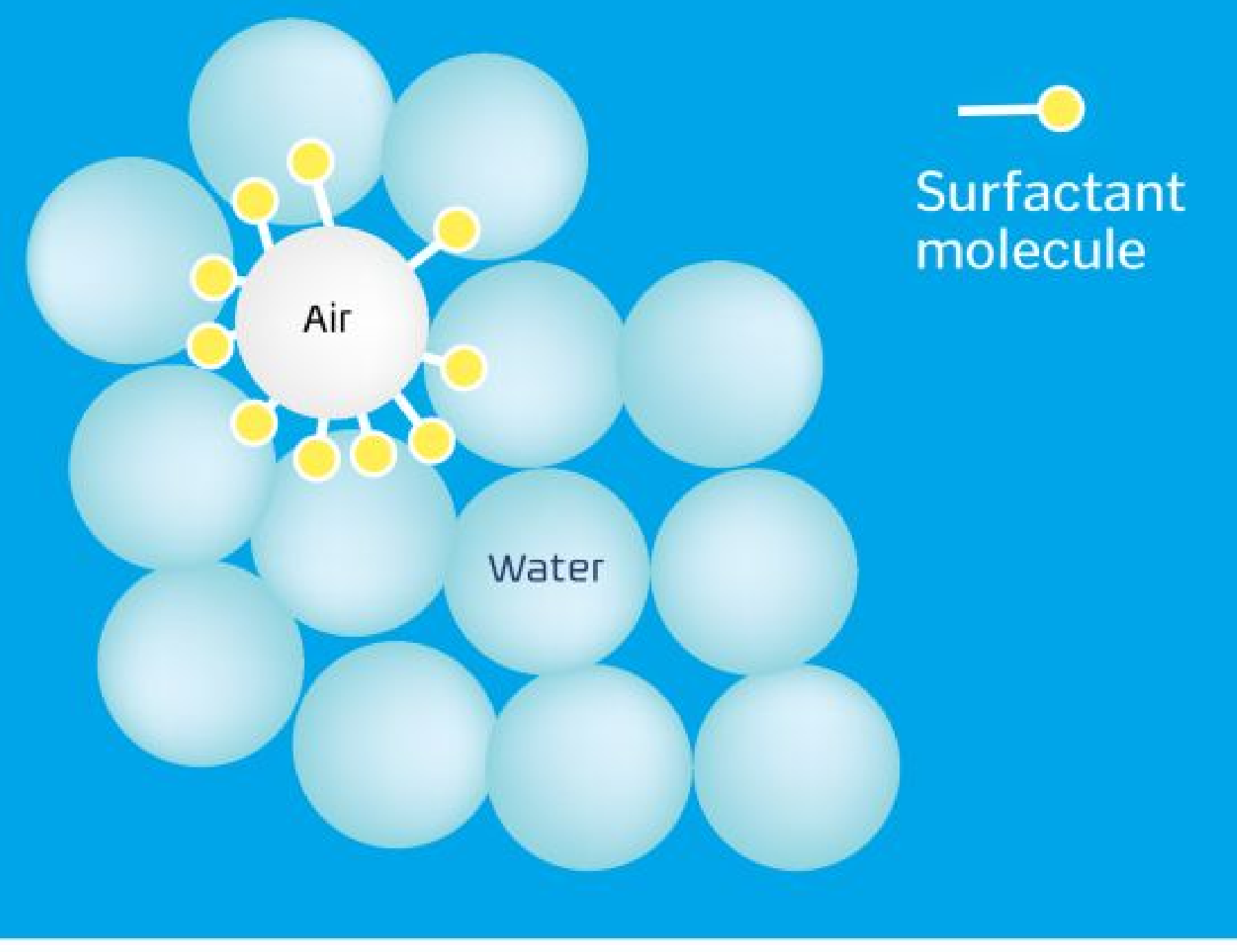
Thanks to science, chefs are able to present flavours in all sorts of interesting textures, including that of foam. To create an edible foam garnish, a surfactant such as egg white, gelatine, lecithin from egg yolk or agar-agar from seaweed is added to a flavoured liquid, and then air bubbles are introduced by shaking, blending or injecting nitrous oxide into the mixture.

The surfactant contains both water-attracting regions that dissolve in the liquid and water-repelling regions, which stick to the air bubbles. This helps to reduce the surface tension of the air bubbles, stopping them from popping or escaping so that foam is formed.

Without surfactant



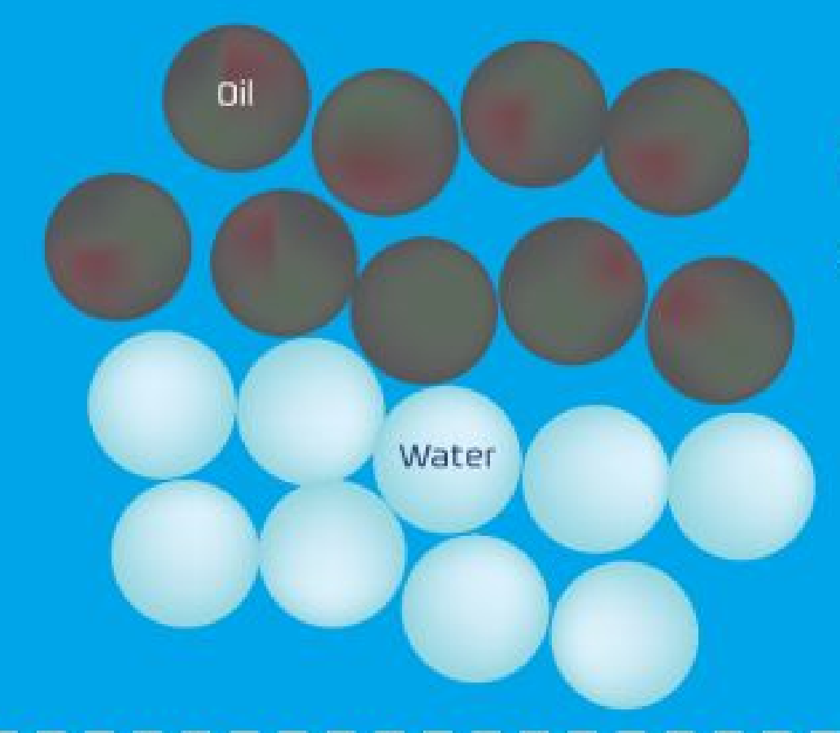
With surfactant



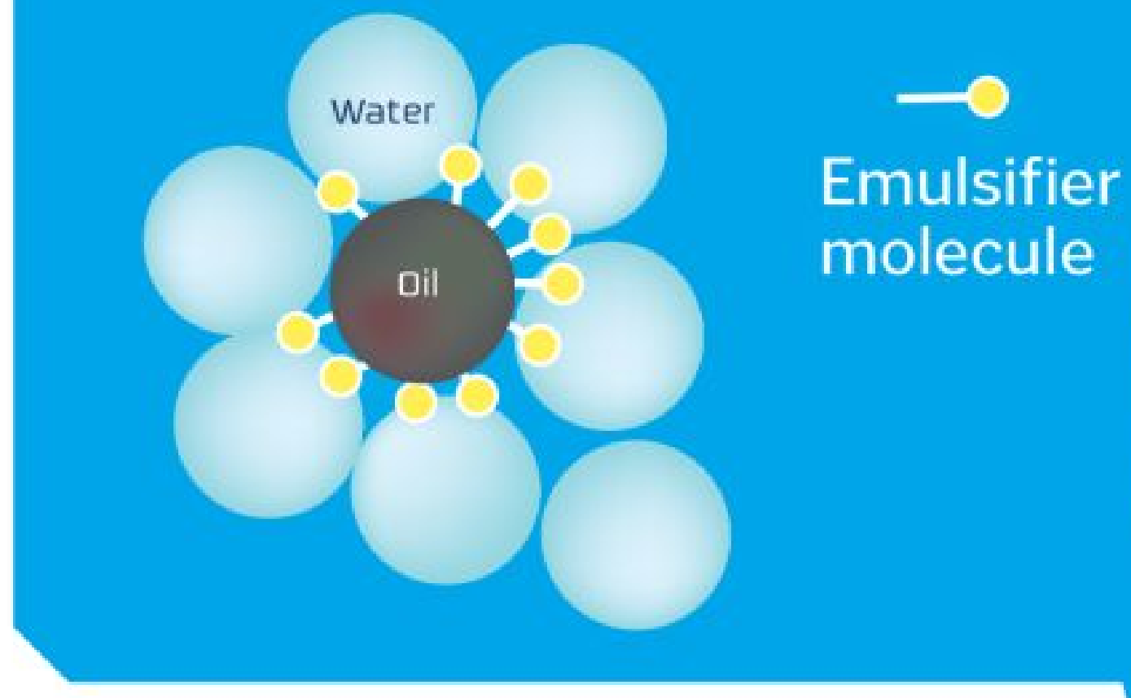
Foam physics takes advantage of a molecule's polar or non-polar properties

Emulsions

Oil and water don't naturally mix, so when a chef wants to create a deliciously creamy sauce in the flavour of their choice, they need the help of a special ingredient. Surfactants, such as egg whites and lecithin from egg yolks, enable the two liquids to mix in the same way they help keep the air bubbles inside edible foam. One part of the surfactant is attracted to the water, while the other is attracted to the oil, so it is able to bind the two together to form an emulsion.



With emulsifier



Fresh bread smell

What creates the aroma of a loaf straight out of the oven?

The mouth-watering smell of freshly baked bread is created by a complex cocktail of chemical compounds produced during the bread-making process. The ingredients used are a source of some of these compounds, but raw dough doesn't smell particularly delicious, so other factors are needed to develop the aroma.

Byproducts of the fermentation process, when yeast converts sugars into carbon dioxide, produce many of the main aroma compounds of the bread's crumb, while the smell and deep brown colour of the crust are created inside the oven. During baking, Maillard reactions between the sugars and amino acids, and caramelisation reactions of the sugar, contribute the final components of the breads flavour and odour. The ratio of ingredients, length of fermentation and temperature of baking all influence the amount of each compound that is created, causing each type of bread to have its own unique aroma.

Some companies sell diffusers and sprays that smell of fresh bread

Freshly baked chemistry

Discover some of the compounds that contribute to bread's delicious aroma

Maltol and isomaltol
These compounds are created as a result of the caramelisation of sugars in the crust and add a sweet aroma.

2-acetyl-1-pyrroline
Formed during baking, this compound produces the roasted, cracker-like smell of the crust of wheat bread.

(E)-2-nonenal
Produced in the crust, this compound also contributes to the odour of cucumbers.

Methional
Found in high levels in the crust and crumb of rye bread, this compound imparts a potato-like scent.

2,3-butanedione
More commonly known as diacetyl, this compound creates the buttery smell of the bread crumb.

Incense

Can burning incense be bad for your health?

People have been burning incense for centuries, whether as part of religious practices or for its pleasant smell. There are two main types: indirect-burning and direct-burning incense, but the latter is more common.

Indirect-burning incense requires a separate heat source, such as charcoal, to burn aromatic ingredients like sandalwood and agarwood, while direct-burning incense comes as a stick with aromatic ingredients adhered to it and burns by itself. These sticks are typically made of bamboo soaked in an adhesive material such as tree resin and coated with herbal and wood powder and fragrance materials. They are used in temples and homes throughout the world, but a recent study has found that they can also be hazardous for your health.

Burning incense releases particle matter into the air, which can then be breathed in and trapped in the lungs. Some of these particles have been found to be highly toxic and contain chemical properties that have been linked to the development of cancers. Therefore, it is advised that burning incense should be done outdoors or in a well ventilated room to reduce exposure and thereby lessen any potential health risks.

Incense burns at a slow and even pace to produce aromatic smoke

© Thinkstock; Shutterstock

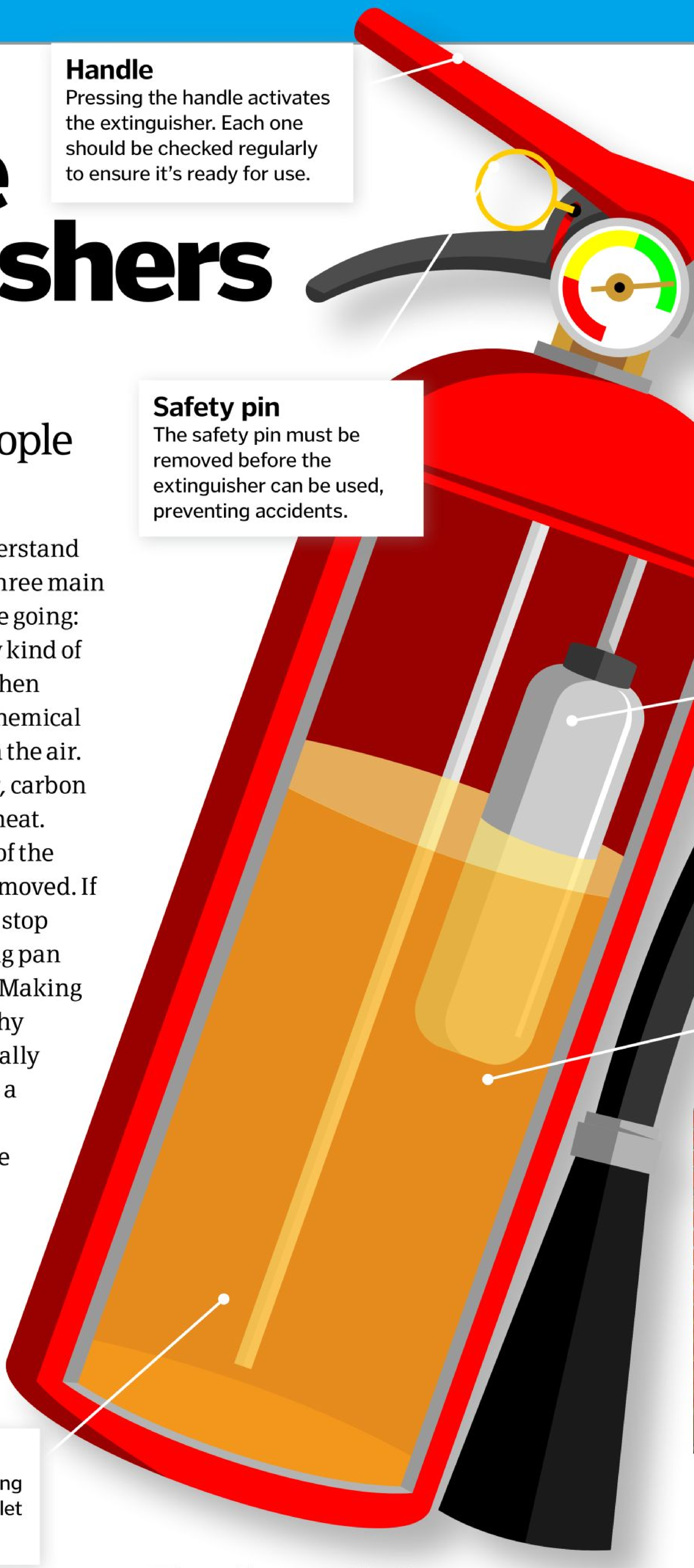
How fire extinguishers work

The science helping people to fight fires fast

To fight fire, first you need to understand what makes it burn. There are three main components that help keep a fire going: fuel, oxygen and heat. Fuels can be any kind of combustible or flammable material. When extreme heat is applied to this fuel, a chemical reaction takes place with the oxygen in the air. This chemical reaction produces water, carbon dioxide, other waste gases and a lot of heat.

In order to put fires out, one or more of the three main components needs to be removed. If you can cut off oxygen to the fire, it will stop burning – that's why covering a burning pan with a fire blanket puts out the flames. Making the fuel cold will also work, which is why throwing water on a small fire will usually put it out. And if you stop adding fuel to a fire then it eventually burns itself out.

Fire extinguishers work well because they remove one or two of these components from the fire. There are different kinds of extinguishers depending on the type of fire you're fighting. Using the right one is important, as is knowing the science behind how they work.



Handle
Pressing the handle activates the extinguisher. Each one should be checked regularly to ensure it's ready for use.

Hose
The water flows out of the siphon tube and into the hose, allowing the user to direct the water onto the fuel of the fire.

Safety pin
The safety pin must be removed before the extinguisher can be used, preventing accidents.

CO_2 canister
When the handle is pressed, the valve to the CO_2 canister is opened, increasing the pressure inside the extinguisher.

Water
When the pressure increases the water is pushed out of the extinguisher via the siphon tube.

Siphon tube
The tube is designed to stop water leaking out of the extinguisher accidentally but let water up it when the CO_2 is released.

Fire extinguishers come in different sizes and are colour coded depending on what extinguisher agent is inside

Extinguisher types

Water

The water quickly cools the fuel, stopping the fire by removing the heat. Spray it directly onto the fuel, not the flames.

For use on…
Wood, paper, textiles etc.

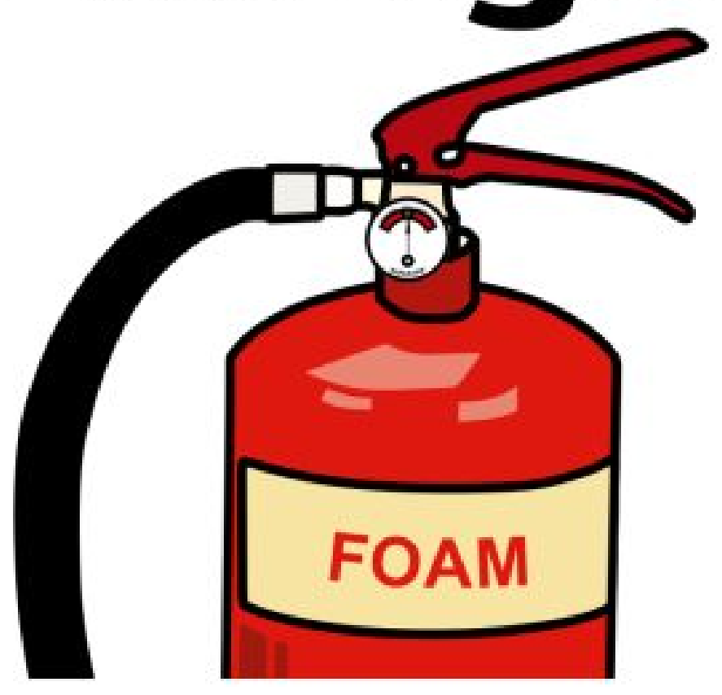
DO NOT use on…
Flammable liquids
Live electrical equipment

Dry powder

This powder, often similar to baking soda, doesn't burn. Instead, it smothers the fuel and removes the oxygen from the fire.

For use on…
Wood, paper, textiles etc.
Flammable liquids
Gaseous fires
Live electrical equipment

DO NOT use on… N/A

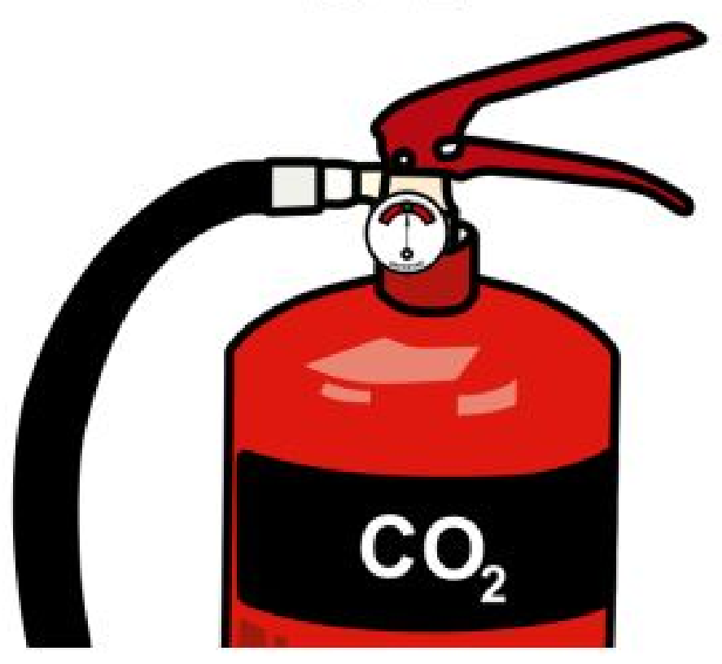


Foam

This foam is similar to the dry powder. When heated, it changes state and releases CO_2 to help smother the fire.

For use on…
Wood, paper, textiles etc.
Flammable liquids

DO NOT use on…
Live electrical equipment



Carbon dioxide

This extinguisher releases CO_2 in gas form. CO_2 is heavier than oxygen, so it displaces the oxygen that is fuelling the fire.

For use on…
Flammable liquids
Live electrical equipment

DO NOT use on…
Do not use in a confined space

Vapourising liquids

Vapour-based extinguishers smother the oxygen that fuels a fire. Extinguishers using halon are largely banned since halon was linked to ozone depletion.

For use on…
Wood, paper, textiles etc.
Flammable liquids

DO NOT use on…
Do not use in a confined space

Wet chemical

The chemical is especially effective for putting out cooking oil fires, as it forms a soap-like solution that smothers the fire.

For use on…
Wood, paper, textiles etc.
Cooking oil fires

DO NOT use on… N/A

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Food preservation

We are in a constant food war with microbes determined to eat our meals

Our lives revolve around food, but so too do the lives of microscopic bacteria and fungi. They are in the air, in the water, on the kitchen counter, and if left unchecked they will bloom and spread throughout our meals, turning edible food into furry mush. And if the microbes aren't at it, molecules called enzymes, present naturally in plants and animals, will also have a good go at breaking some foods down, and oxygen will gradually turn fats rancid. Therefore, food preservation has one fundamental goal: to stop, or at least slow down, this process.

Pickling
Vinegar is acidic, and this causes serious problems for microbes. The acid affects their molecular machinery, twisting their enzymes out of shape and stopping them from functioning properly. Without enzymes, life quickly comes to a halt.

Desiccation
Removing moisture from foods makes them unpleasant places to live. The aim is to get the water content down to below 25 per cent, at which point lots of microorganisms will struggle to survive. All life on Earth needs water.

Canning
Putting food inside a sealed container and heating it to kill any microbes is a really effective method of preservation. Once the contents of the can have been sterilised, nothing can get in to start breaking the food down.

Freeze-drying
This is a step up from normal drying. Rather than heat the food to evaporate the water, it's frozen first and the ice is converted to gas in a process called sublimation. This helps to keep the structure of the food intact.

Freezing
Taking the temperature of food below zero doesn't kill microbes, but it does slow them down. They enter a state of suspended animation, and don't reproduce until they're warmed up again. But freezing food too slowly can create ice crystals.

> "If left unchecked, bacteria and fungi will bloom and spread throughout our meals"

Smoking
This preservation method has a combination effect. Heat kills microbes, and the chemicals in the smoke itself slow or stop their growth. And, as the food smokes, it dries out, removing some of the water that organisms need to survive.

Fermentation
It might sound counter-intuitive, but this preservation method works by actually allowing microbes to break foods down. Some yeasts and bacteria are safe to eat, and they produce acid or alcohol that help to stop the growth of nasty bacteria.

Vacuum-packing
This method works by removing air from around the food – like us, some microbes need oxygen. However, some can survive with very little, so vacuum-packing needs to be combined with other preservation methods to make sure the contents stay safe.

Sugaring
Soft summer fruits can become fuzzy with mould in a matter of hours, but sugar helps keep them edible for months. It works in a very similar way to salting, but with sugar, the end result is a sweet treat-like jam.

Salting
This ancient preservation method works by dehydrating microbes. The salt draws water out of their cells, stopping them in their tracks. It also interferes with the molecular machinery that microorganisms need to survive. However, some microbes can tolerate more salt than others.

Chemical preservation

Many preservatives change the taste and texture of foods, but there is another option that's widely used in prepackaged products. These are chemical preservatives, and they don't just keep food fresh, they also help to preserve its colour and taste.

There are three main types: antimicrobials stop the growth of microorganisms, antioxidants stop fats going rancid, and the others help to destroy enzymes.

Common preservatives include sulphur dioxide, which is responsible for keeping dried apricots orange. Nitrates and nitrites are used to preserve meats like bacon. And ascorbic acid (vitamin C) can help to stop fruits turning brown after they've been cut.

Processed foods often have preservatives added to help them last longer

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Hazmat suits

The clever pieces of kit that protect us from invisible dangers

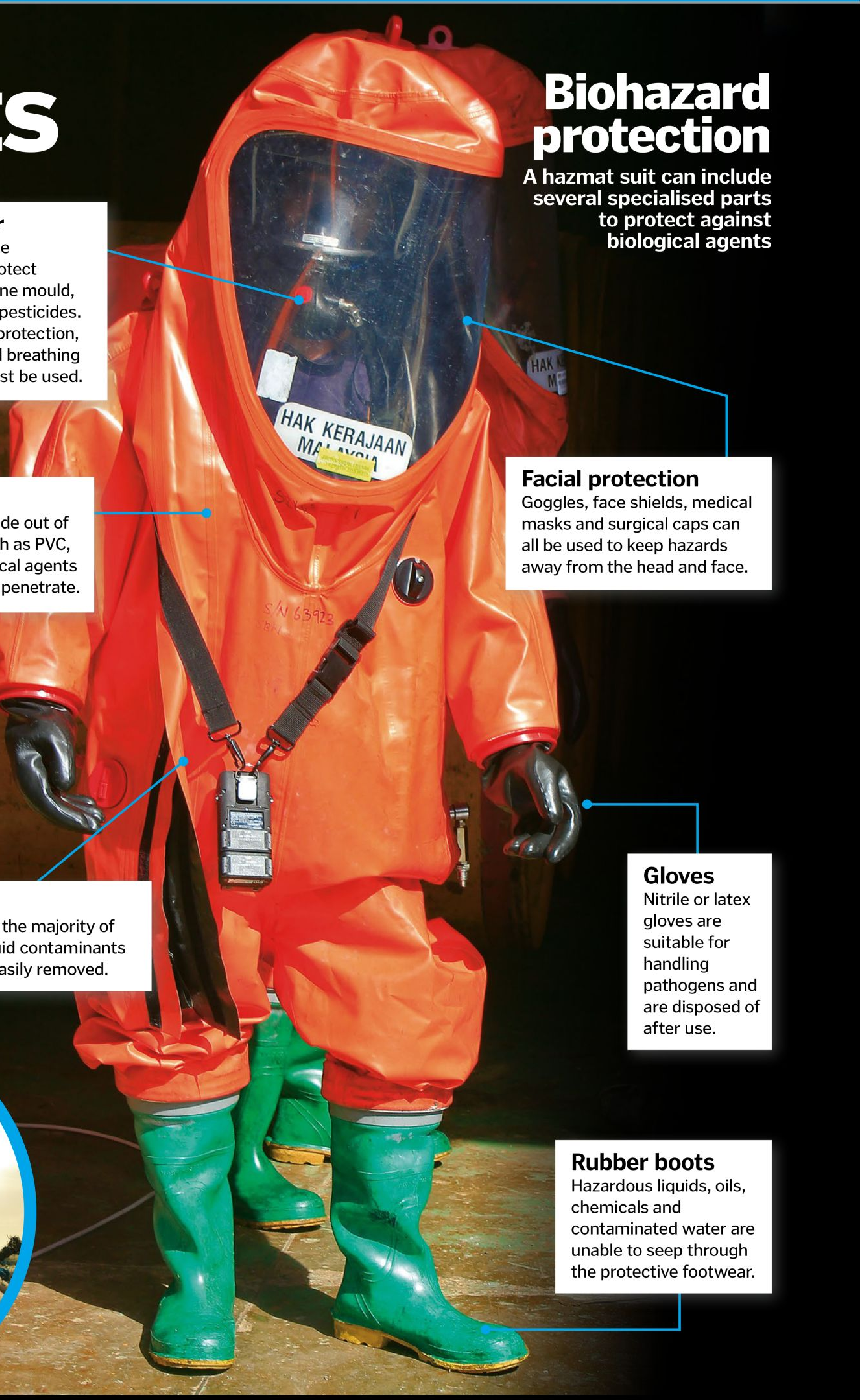
For every weapon forged there is a piece of armour made to defend against it. For swords it was chainmail, for bullets it was Kevlar, and for chemical agents it's the hazmat suit. Short for hazardous materials suit, this piece of kit is built to defend us both on and off the battlefield by shielding us from harmful liquids and gases.

A barrier formed of plastic, fabric and rubber, along with an independent source of oxygen, hazmat suits protect workers by separating them from their hazardous environment. Simpler suits can be slipped on to protect against harmful liquids, but more advanced suits can become completely airtight to defend against airborne contaminants and toxic chemicals. This versatility has meant that hazmat suits can be used by the military, in industry and by healthcare workers.

Workers operating in waste disposal make daily use of hazmat suits, and they're used by staff in nuclear power stations to ensure they don't carry any radioactive contaminants home at the end of the day. Recently, nurses and carers treating patients infected with the Ebola virus in West Africa wore hazmat suits to protect themselves against airborne infection.

These examples are just a few of the many ways hazmat suits can keep us safe by protecting our skin, eyes and respiratory system.

Workers collecting recyclable material from landfills need to protect themselves



Biohazard protection

A hazmat suit can include several specialised parts to protect against biological agents

Respirator
Full or half face respirators protect against airborne mould, asbestos and pesticides. For chemical protection, self-contained breathing apparatus must be used.

Facial protection
Goggles, face shields, medical masks and surgical caps can all be used to keep hazards away from the head and face.

Overalls
These are made out of materials such as PVC, which biological agents are unable to penetrate.

Gloves
Nitrile or latex gloves are suitable for handling pathogens and are disposed of after use.

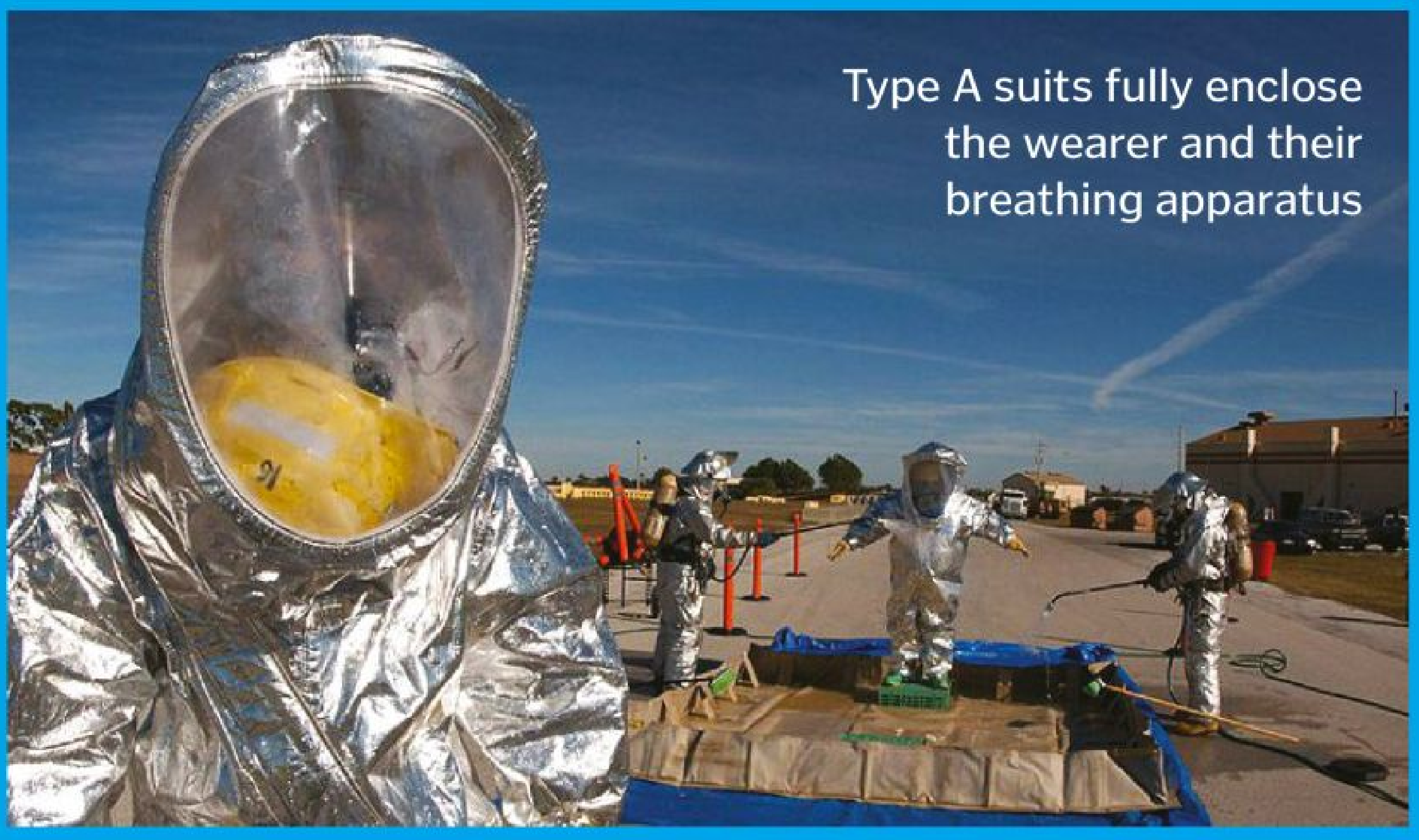
Apron
This catches the majority of solid and liquid contaminants and can be easily removed.

Rubber boots
Hazardous liquids, oils, chemicals and contaminated water are unable to seep through the protective footwear.

Levels of protection

The term 'hazmat suit' covers a wide spectrum of protective clothing. Anything capable of blocking hazardous materials may be labelled as a hazmat suit, but a brewer working with a liquid disinfectant would be dressed quite differently to a scientist handling toxic gases. So to ensure the appropriate amount of precaution is taken, hazmat suits are arranged into four different types.

Type A suits are fully concealed from the outside and are equipped with a self-contained breathing apparatus. By ably defending against biological and chemical hazards, they are the go-to choice when working in dangerous atmospheres. Type B suits are not airtight but retain breathing equipment, so can be used when handling gases that aren't harmful to the skin. Type C suits are used when working with general biohazards, and include a respirator. Finally, Type D suits would be worn by our brewer, and could simply include a protective apron, boots, glasses and long gloves.



Type A suits fully enclose the wearer and their breathing apparatus

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Life in the lab

Discover the experiment that set out to simulate the origins of life

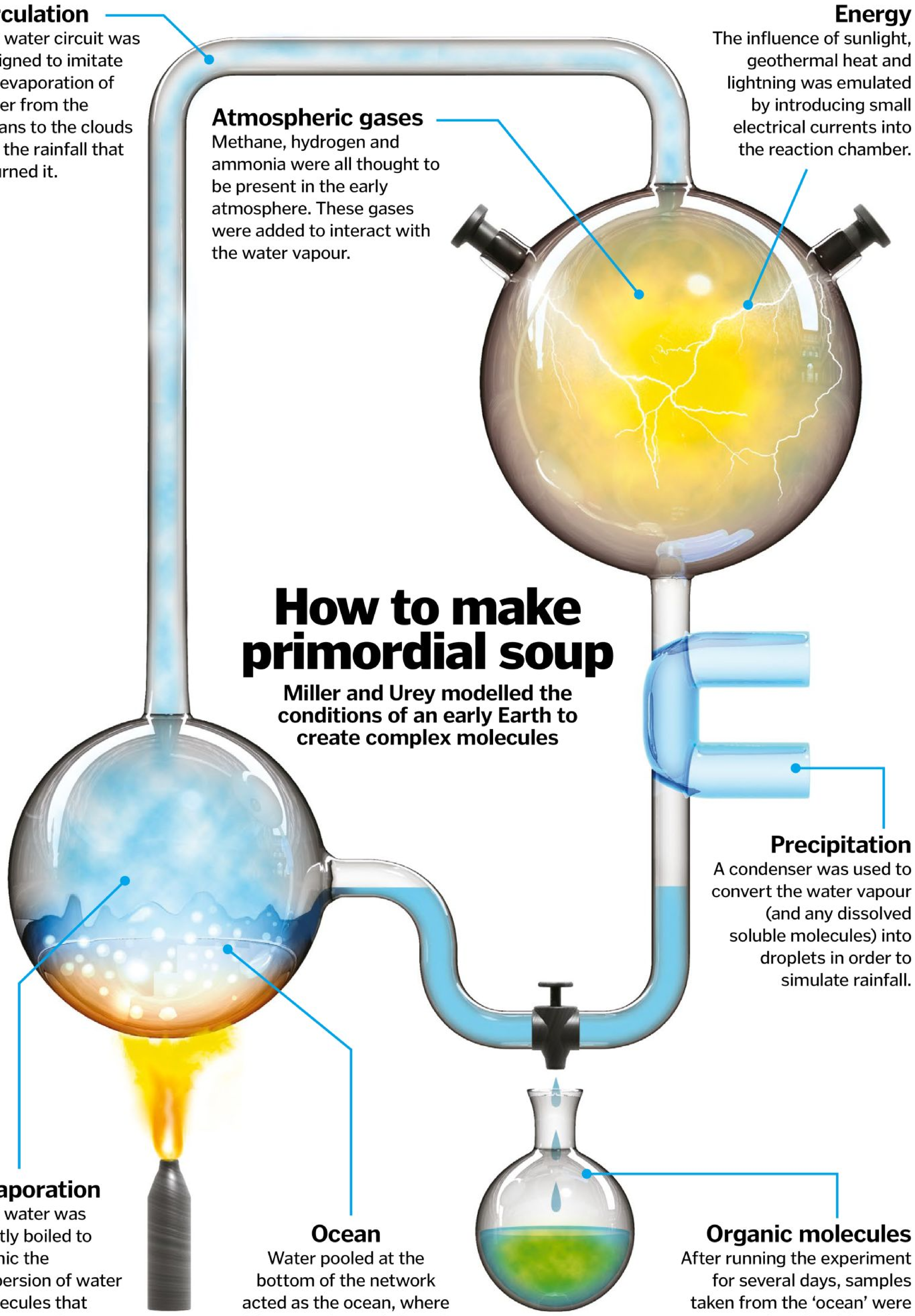
After a series of experiments in the 1860s, Louis Pasteur described the law of biogenesis, which explains that all lifeforms come from other lifeforms. Not long before that, Charles Darwin had published his theory of evolution, explaining how complex life evolved from simple organisms over millions of years. Both theories answered a lot of questions, but one piece of the puzzle was still missing – how exactly had life started in the first place?

An answer was suggested in 1924 by Russian biochemist Alexander Oparin, who described the early oceans of Earth as a 'primordial soup'. He believed that the seas had been full of complex molecules. These included the building blocks of life such as amino acids and other organic compounds, which would later react and combine with other molecules to form the first cells. Scientists knew that these building blocks could be made inside living things, but Oparin believed that at first, they had been formed solely by chemical reactions.

In 1952, American chemists Stanley Miller and Harold Urey set out to show how these building blocks had found their way into the soupy seas. They set up a lab experiment that replicated the conditions of the oceans found on early Earth; using water, gases and electricity inside a network of flasks and tubes, the two scientists built a circuit that emulated the atmospheric composition, the water cycle and frequent lightning strikes. After a week of running this experiment the pair made an amazing discovery; the simple molecules had reacted to form many complex molecules, including amino acids, all by chemistry alone.

How to make primordial soup

Miller and Urey modelled the conditions of an early Earth to create complex molecules



Circulation
The water circuit was designed to imitate the evaporation of water from the oceans to the clouds and the rainfall that returned it.

Atmospheric gases
Methane, hydrogen and ammonia were all thought to be present in the early atmosphere. These gases were added to interact with the water vapour.

Energy
The influence of sunlight, geothermal heat and lightning was emulated by introducing small electrical currents into the reaction chamber.

Precipitation
A condenser was used to convert the water vapour (and any dissolved soluble molecules) into droplets in order to simulate rainfall.

Evaporation
The water was gently boiled to mimic the dispersion of water molecules that occurs on the ocean's surface.

Ocean
Water pooled at the bottom of the network acted as the ocean, where life on Earth was believed to have begun.

Organic molecules
After running the experiment for several days, samples taken from the 'ocean' were analysed and found to contain amino acids.

Inconclusive results

Since Miller and Urey conducted their ground-breaking experiment, we have a better understanding of the conditions of early Earth. Analysis of ancient rocks has revealed that atmospheric conditions were different to those modelled in the experiment. There, air was richer in carbon dioxide and nitrogen, with only trace amounts of other gases. Repeating the experiments with this more realistic mixture is unlikely to produce amino acids.

Other scientists have cast doubt on the likelihood that amino acids would directly lead to the building blocks of life. Nucleic acids that form RNA and DNA, molecules that can make copies of themselves, are much more difficult to create. Scientists estimate that the production of these kinds of molecules would require a lot of energy and catalysts, molecules that speed up reactions. Hydrothermal vents on the sea floor are now considered to be a more likely location for the origins of life. The chemicals and heat found at these deep-sea chimneys could potentially provide the necessary conditions for life to emerge.

The conditions on an early Earth are now thought to be rather different to Miller and Urey's initial predictions

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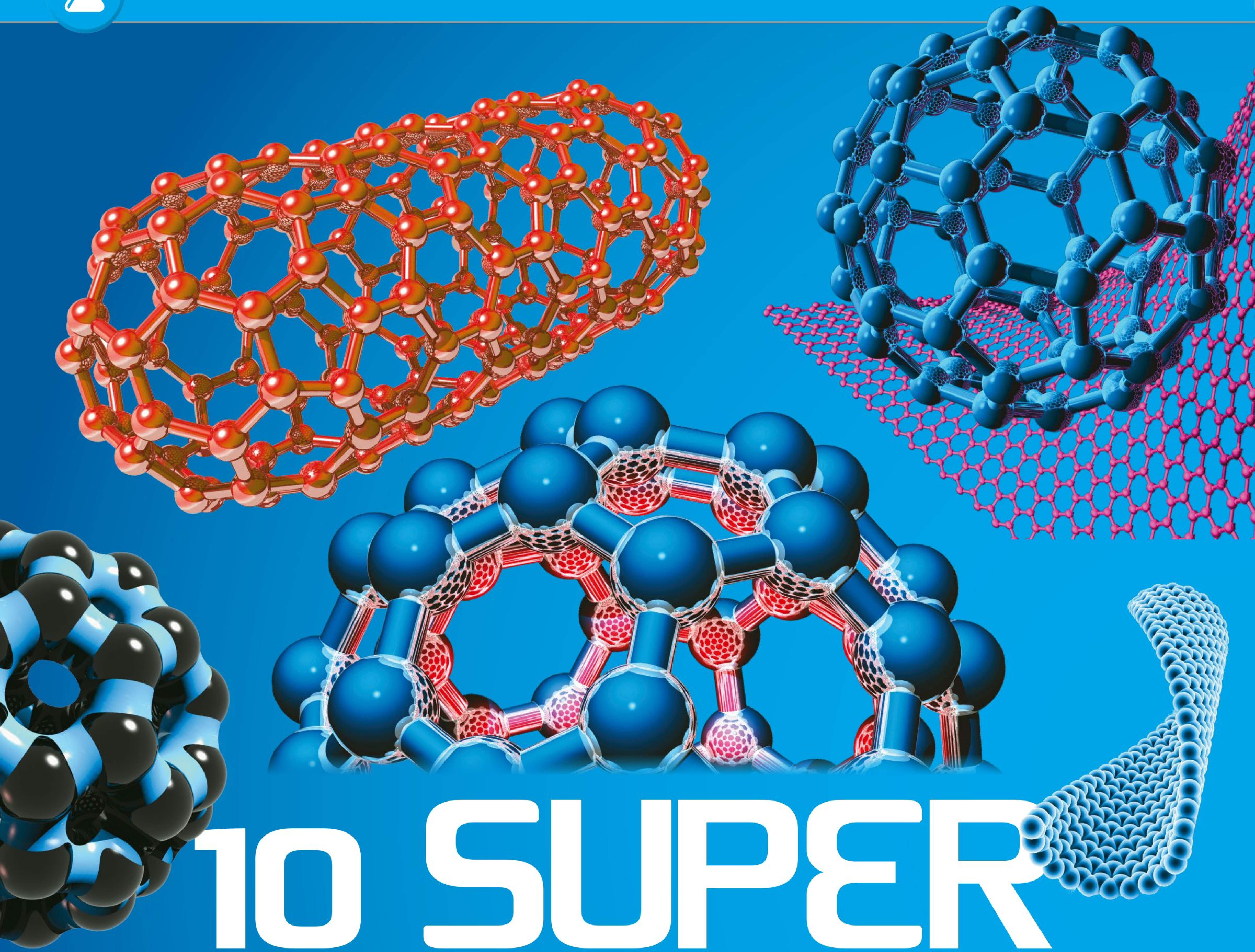


10 SUPER MATERIALS

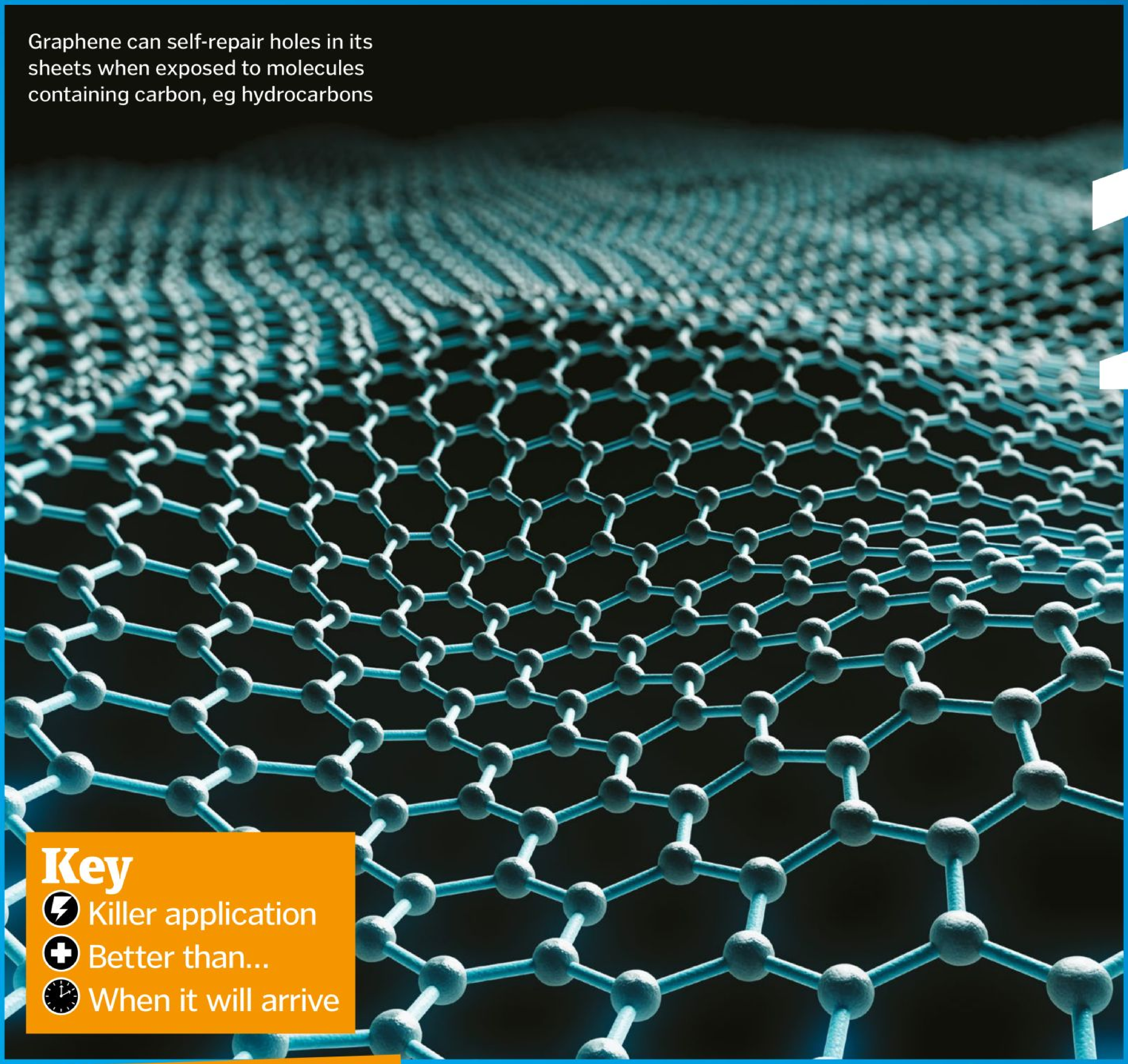
How are we enhancing Mother Nature's design to develop the new-and-improved materials tomorrow's world will be made of?

With natural resources dwindling and some no longer meeting our needs, a new range of 'super materials' are now being developed in labs around the world. Designed to increase efficiency, these substances are new compounds that build upon and improve what's currently available, to be the best in a particular field.

Natural materials have been used for decades and even centuries to perform many day-to-day tasks, from conducting electricity to insulating heat, but super materials take things to a whole new level. The emphasis is now geared towards the best and only the best. Nothing less than total conduction, extreme strength or complete insulation will do. Essentially these materials will do the job better than anything that has gone before.

Whether it's based on an existing natural substance or an improvement on previous man-made efforts, super materials look to become increasingly important in a world searching for sustainable and greener energy sources. However, many questions still remain. Can we harness these materials and mass-produce them? Will they be available to the general public? Are they as good as they seem?

Over the following pages we present our pick of ten of the most impressive super materials that look set to reshape our future.

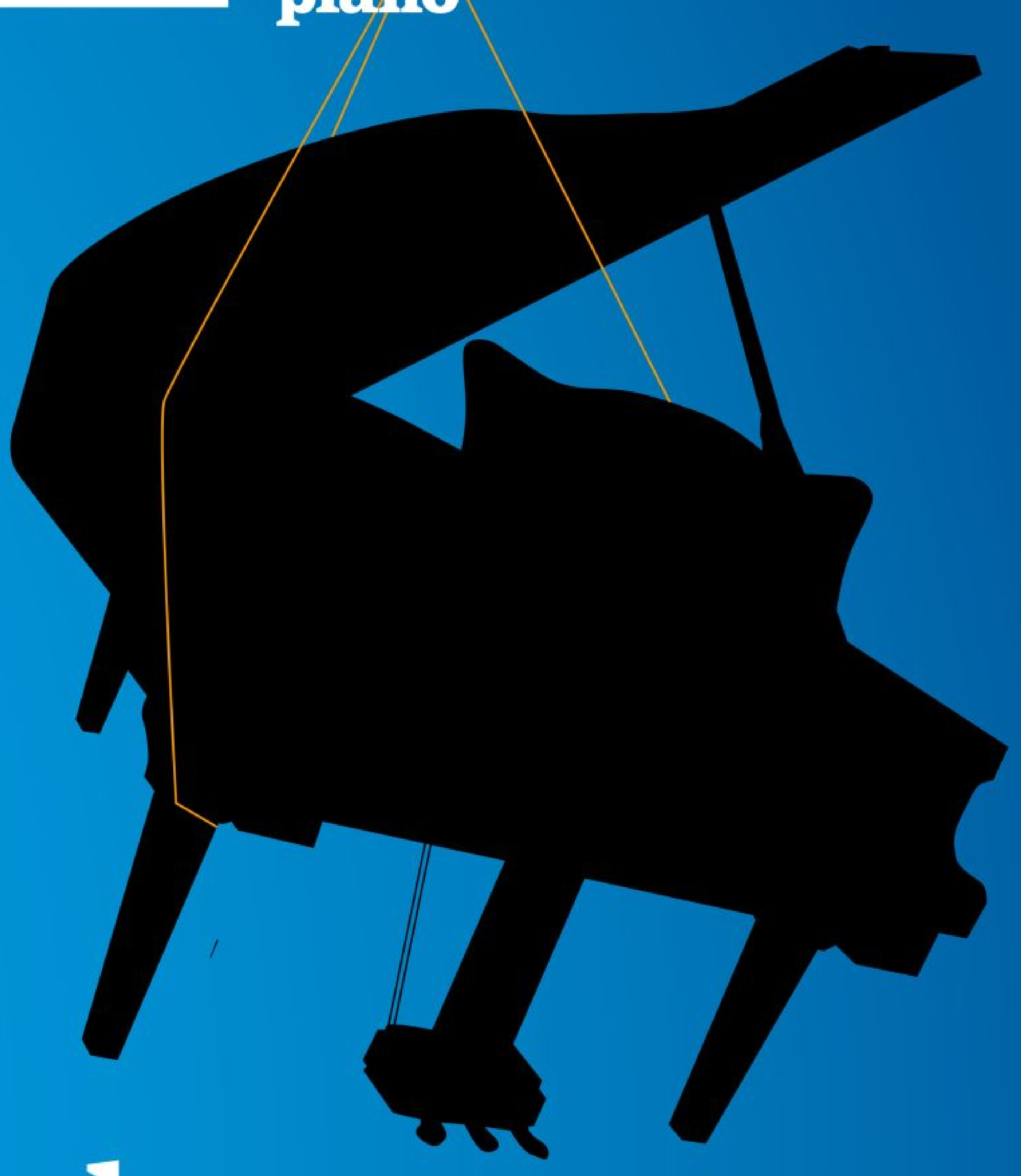


Graphene can self-repair holes in its sheets when exposed to molecules containing carbon, eg hydrocarbons

Key
⚡ Killer application
✚ Better than…
🕒 When it will arrive

1 grand piano

A strand of graphene as fine as a pencil point can hold up a 450kg (1,000lb) piano



GRAPHENE Stronger than diamond

If super materials had a poster boy, graphene would be it. Composed of a single layer of graphite carbon atoms in a honeycomb pattern, its structure is stronger than diamond. It was first theorised as far back as the mid-20th century but only gained recognition for its astonishing properties when Andre Geim and Konstantin Novoselov experimented with it and went on to claim a Nobel Prize in 2010.

Graphene is famed for its excellent conduction of both heat and electricity. Atomic force microscopy has proved it is, at the very least, 100 times stronger than steel and can be stretched by up to 20 per cent of its own size. It has been used for all manner of things, such as a coating material to nullify lightning strikes, increasing energy storage in batteries and making touchscreens more responsive.

Its coating properties in particular help stop corrosion and prevent micro-organisms from spreading. The electrons within it travel at a hundredth the speed of light as if they carry no mass. Graphene's tiny size makes it ideal for small electronic devices, as its high thermal conductivity enable them to dissipate heat while still maintaining power.

Graphene is also actually the source of many other super materials and is the parent form of carbon nanotubes and buckyballs. However, it was only experimentally isolated on its own accord in the 2000s by the aforementioned Nobel Prize winners.

There are currently only a few ways of producing graphene: mechanical or thermal exfoliation, chemical vapour deposition and epitaxial growth. None of these methods are exactly geared for production on a large scale, so a new way of creating the super material has been proposed. This involves oxidising the graphene that turns it into graphene oxide, which is easier to contain and transport. However, this method is still in its early stages.

Adding this simple carbon allotrope to a variety of surfaces and devices is surely the future as the human race looks to establish ever-more efficient materials. Some are sceptical of the potential of this substance and it's admittedly hard to believe that one material can have so many impressive properties, but graphene undoubtedly still has much to offer.

⚡ Counteracting lightning strikes
✚ Copper wires at conducting electricity
🕒 Already around, with its uses increasing

Five ways we can use graphene

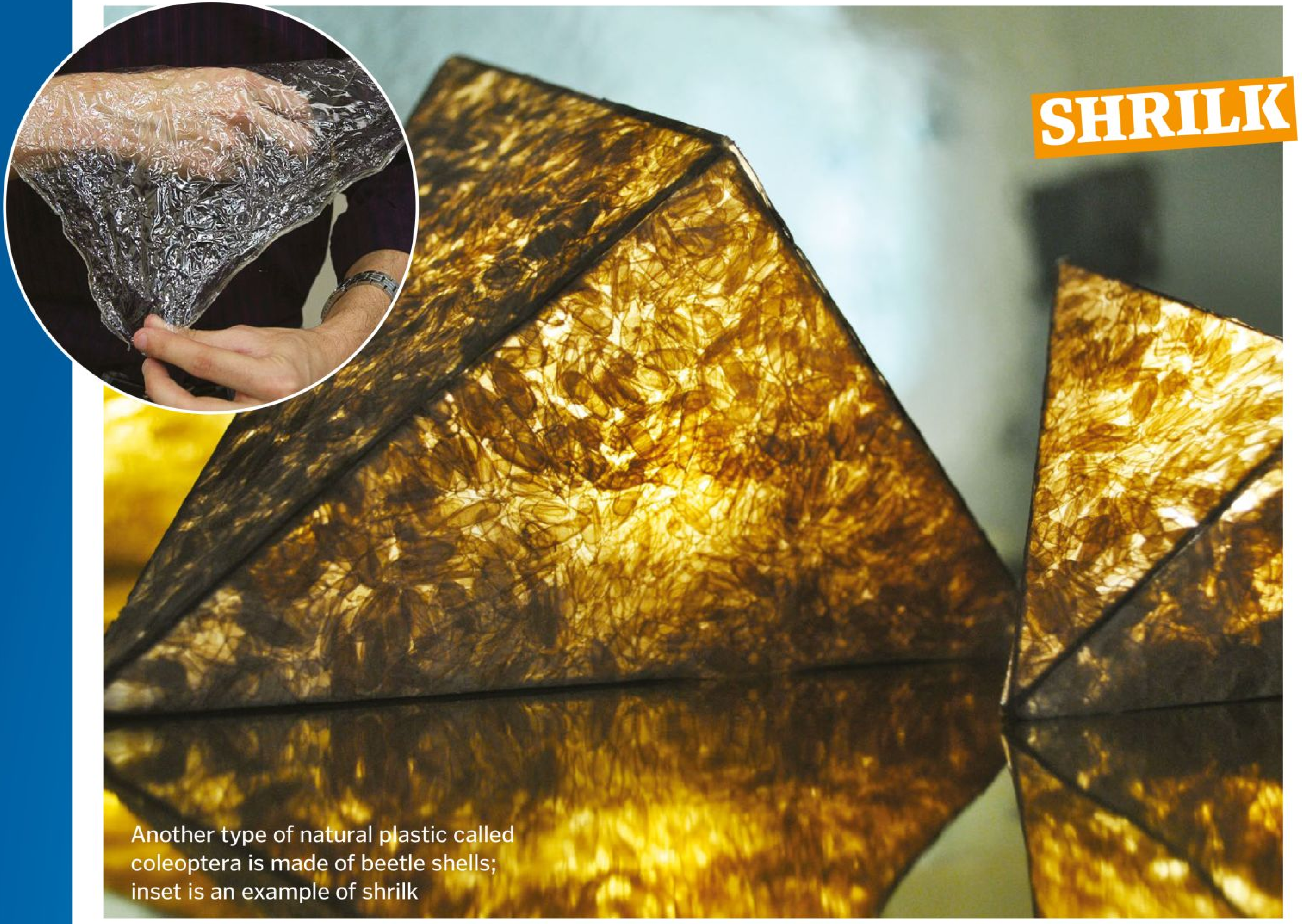
1. Lightning catcher
Outstanding electrical conductivity means it can not only nullify lightning, but perhaps even harness it. This has never been done, but graphene could be the material for the job.

2. Wires
Copper wires are found in all electrical circuits, but graphene can transport 1,000 times the density of copper. Increasing electrical efficiency would cut emissions and fuel use.

3. Coatings
Graphene is useful at creating composite materials and can coat plastics or metals to improve their properties, such as electrical conduction or strength.

4. Touchscreens
Handy for touchscreens on smartphones and tablets, graphene is transparent and can transmit 97.7 per cent of light. Its strength also sees off scratches while keeping flexibility.

5. Bio-engineering
Experts suggest the material could have the capability to monitor glucose and cholesterol levels, as well as aid tissue rejuvenation and even cancer treatments.


Another type of natural plastic called coleoptera is made of beetle shells; inset is an example of shrilk

SHRILK

The next generation of plastics

Composed of silk proteins and shrimp shell, shrilk combines biodegradability with excellent flexibility and strength. Based on similar substances in the animal kingdom, shrilk's roots lie in the material found in shells and insect wings. The hope is that the material can replace plastic, which would lessen the impact and size of landfill sites. Like plastic, it's inexpensive and can be used to make clothing, bags and many other everyday products.

In addition to shrilk, there has also been progress with another plastic formed from dead beetle shells – known as coleoptera. This contains chitin, a natural polymer that boasts the light weight and flexibility of conventional plastics but breaks down far more easily.

Shrilk and other biodegradable plastics are great examples of where the fields of biology and engineering create the ultimate material solutions.

- ⚡ Potential to replace plastic
- ✚ Lighter than aluminium and equally strong
- 🕒 More research needed to be mass-produced

Strongest magnet in the world

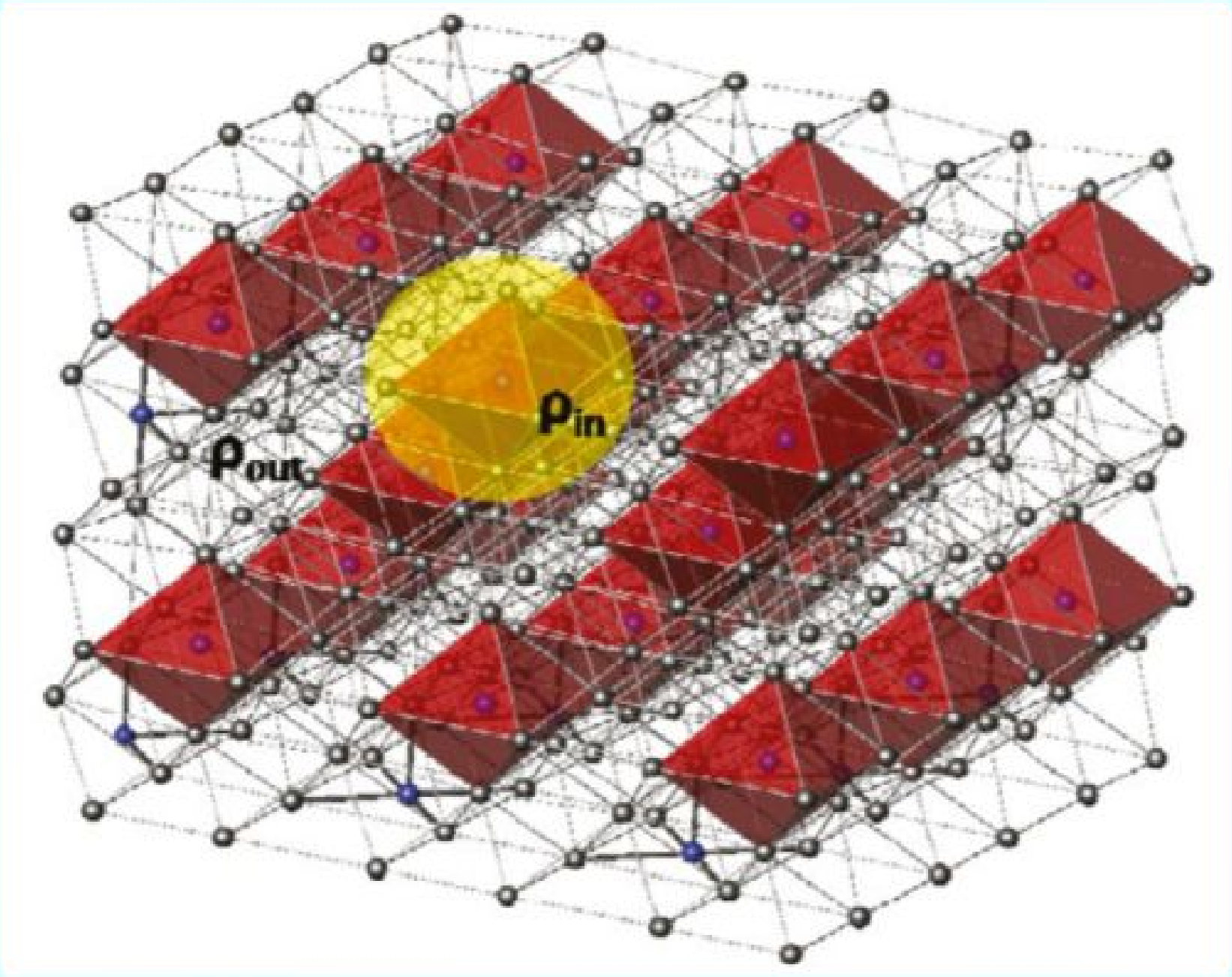
IRON NITRIDE

The most magnetic material on Earth is a mix of iron and nitrogen with the chemical symbol $Fe_{16}N_2$. It's claimed that the material has the strongest saturation magnetic flux density of any man-made substance. This means that the strength of magnetism is the most per unit of molecule within the iron nitride, making it hugely magnetic over its entire surface. Powered by ferromagnetism, iron nitride is electrically uncharged but that doesn't affect its power.

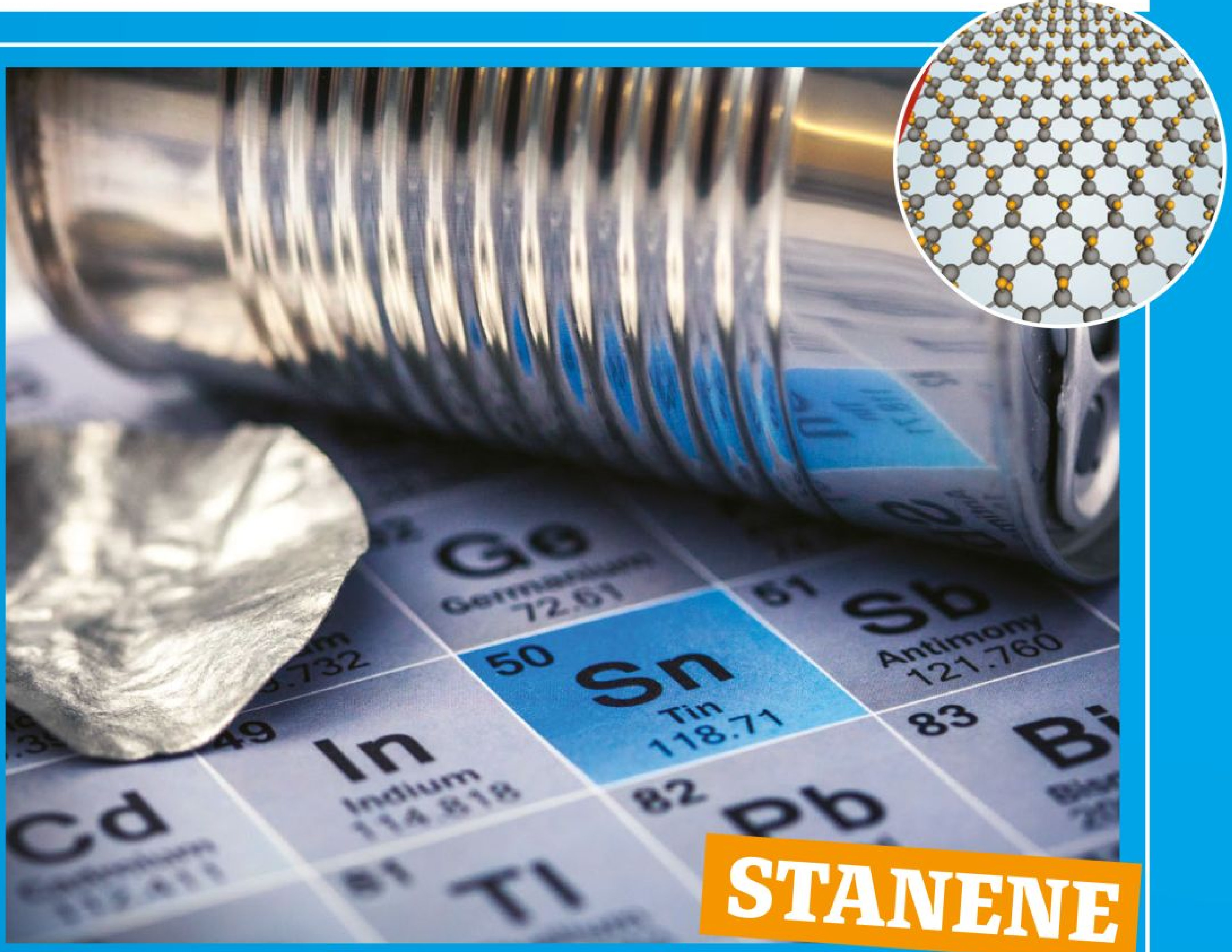
Every electron within the material acts like a tiny magnet. The Fe-N clusters increase electron contact, which intensifies the charge. It's so magnetic that it exceeds the predicted limit of magnetism for a single material. Iron nitride has taken over from the previous holders, neodymium and iron cobalt, to claim the plaudits for the most magnetic material on Earth. It's at least twice as magnetic as its rivals (rated at 130 megagauss oersteds).

Magnets of this magnitude are used in industry and engineering to increase the efficiency of power-production. They are often used as electromagnets within transformers, for example.

- ⚡ Making disk drives more effective
- ✚ Neodymium and iron cobalt
- 🕒 Still in the testing stages – watch this space



> "High magnetic fields play a critical role in developing new materials that affect nearly every modern technology. The vast scope of work currently underway includes the study of new superconductors with the potential to revolutionise how power is stored and delivered. There's also a search for new medicines and analysis of petroleum samples that could lead to better oil extraction"
>
> **Greg Boebinger, director at the National High Magnetic Field laboratory, Florida State University**



STANENE

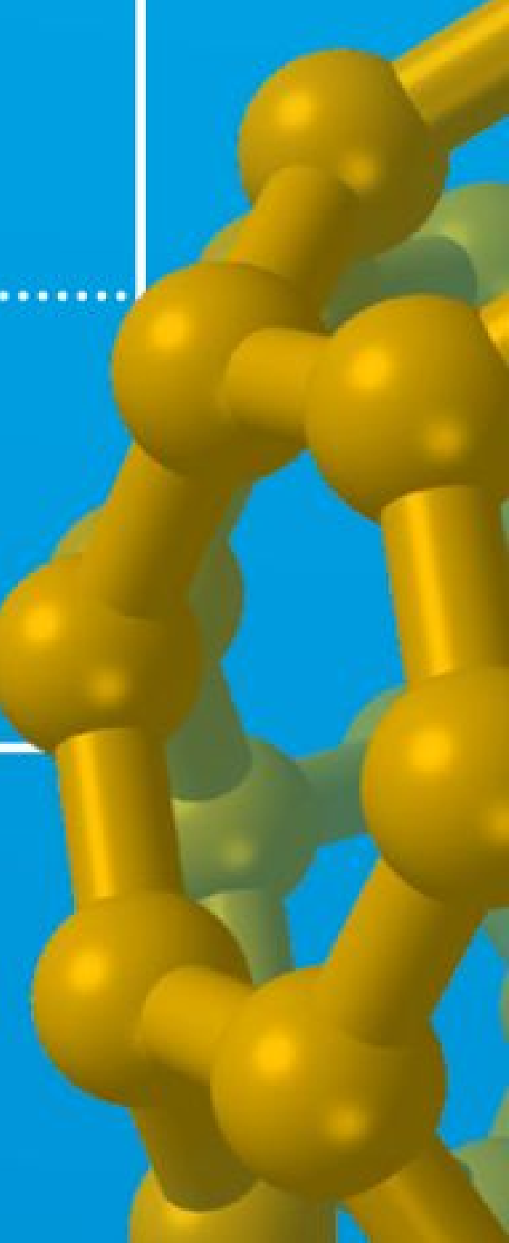
The perfect conductor

Composed of a single layer of tin atoms, stanene is said to be able to conduct electricity with 100 per cent efficiency at room temperature.

This astonishing electrical conductivity has seen it dubbed by some as the new graphene and it's expected to play a big role in the future of computer chips.

Stanene is part of a group of topological insulators that conduct electricity only on their outer edges. Being only an atom thick, the electrons can travel through the material with no resistance, which improves efficiency. However, stanene is the first of these topological insulators to work at room temperature. Difficult to produce due to its minuscule size, the material is still in the developmental stages. There's also talk of adding in a layer of fluorine to increase conduction efficiency at higher temperatures as well.

- ⚡ Boosting the processing speed of computer chips
- ✚ Potentially even graphene
- 🕒 Far from wide-scale production



SUPER-HYDROPHOBIC MATERIALS

The hydrophobic qualities of plants like nasturtiums have been applied to glasses in traffic control units, medical slides and circuit boards (inset)

Completely waterproof

Man-made waterproof materials have paled in comparison with natural examples such as the lotus leaf and insect wings – until now. Known as the most waterproof material ever, super-hydrophobic surfaces have been developed at the Massachusetts Institute of Technology (MIT) and are inspired by butterfly wings and nasturtium leaves.

Often referred to as the lotus effect, nature's waterproof materials defend themselves from water through a special structure. They are covered by bumps or hairs that when exposed to liquid can direct it away from the body. Various man-made materials have taken advantage of this technique, including synthetic silicon, polymer microposts and electro-deposited copper. These coatings, like the organic inspiration, enable water droplets to bounce off a surface to keep it dry. The materials have small ridges that break up the water on the surface and disperse it before it can soak through.

Some of these materials are being pushed even further, with efforts to make them repel ice and snow too. Hydrophobic materials are perfect for everything from clothing to tents and vehicle coatings.

⚡ A de-icer that will rapidly clear snow and ice
✚ Lotus leaves have finally been surpassed
🕒 Already available in clothing and more

"To be super-hydrophobic, a material requires both hydrophobic chemistry and roughness. The trapped layer of air, under certain situations, may act to reduce the drag on an object passing through water" **Michael Newton, Nottingham Trent University**

BUCKYBALLS

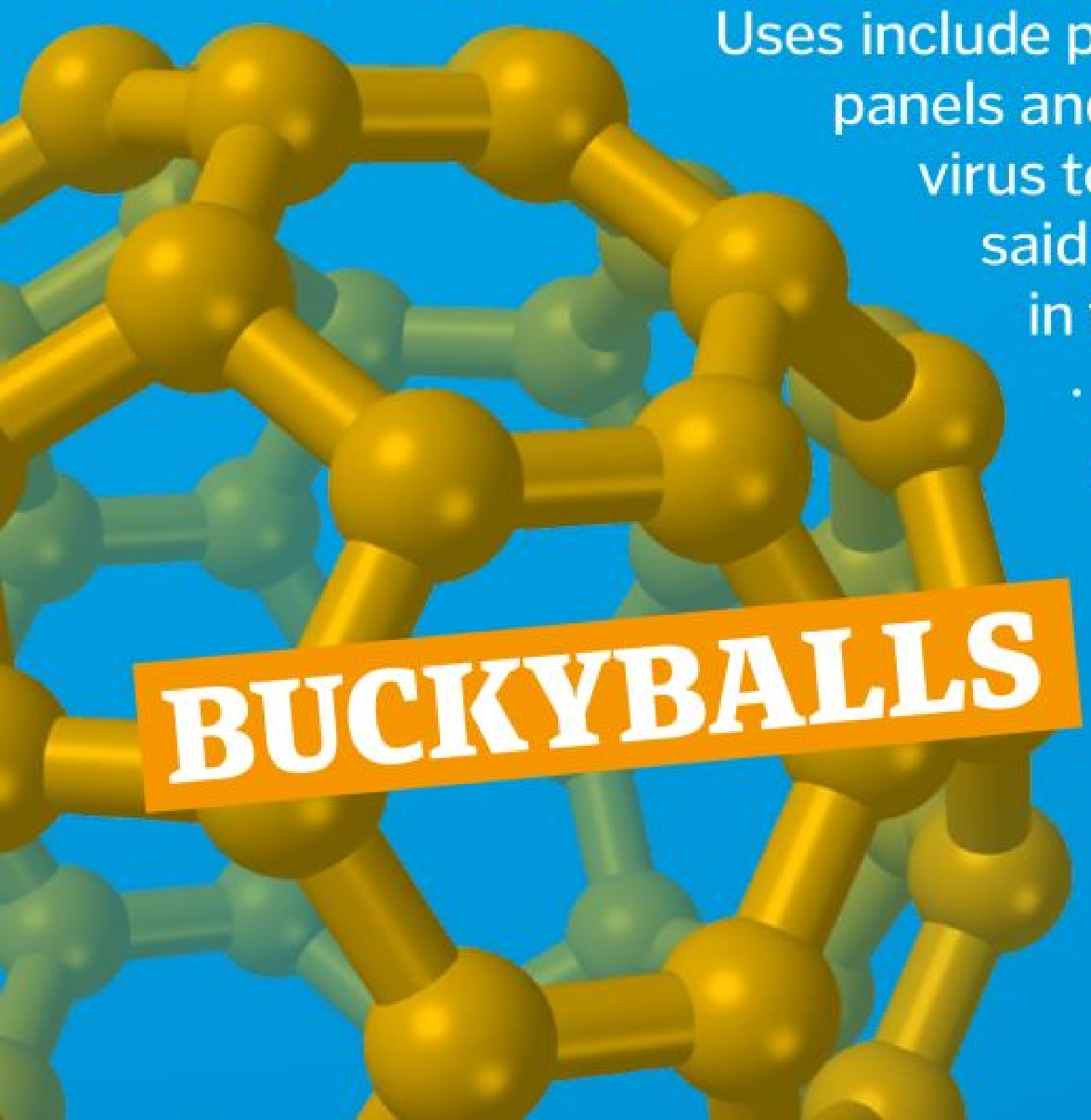
The original super material

Affectionately known as buckyballs, buckminsterfullerene is one of eight carbon allotropes that include diamond, graphene and carbon nanotubes. Discovered by accident, buckminsterfullerene can be considered the daddy of super materials. Its discovery paved the way for the modern era of nanotechnology and proved that materials with extreme properties could be found and worked on. It has led to the discovery of carbon nanotubes as scientists were encouraged to enhance carbon allotropes further in the search for the next carbon nanomaterial.

The allotrope is shaped a bit like a football, with a hexagonal and symmetrical polyhedral structure. A tough skeleton of 60 carbon atoms makes buckminsterfullerene even stronger than diamond under certain conditions. Every carbon atom within this super material also has three bonds, resulting in its incredible strength.

Uses include photovoltaic applications in solar panels and the inhibition of a protein in the HIV virus to stop it replicating. Some have even said it could limit oxidative stress of cells in the body that cause ageing.

⚡ Could combat HIV and cancer
✚ Diamond when tested for hardness under high pressure
🕒 Widely used since 1985



"Superglue is a polymer-based adhesive of the cyanoacrylate type that is polymerised upon contact with a surface and moisture. Some of the uses of these adhesives can be in the form of coatings, fillers, forensics, or even for medical uses like closing [open] wounds"

Rigoberto Advincula, professor of macromolecular science and engineering at Case Western Reserve University, OH, USA

MOLECULAR SUPERGLUE

Most adhesive glue

First there was glue, then there was superglue, but now there is molecular superglue. From the cyanoacrylate (instant glue) family of adhesives, it is designed to be the most adhesive material on the planet and will primarily be used to fight disease.

Genetically engineered from proteins, the glue is polymer-based and formed from nanotechnology that bonds molecules together to form tough covalent bonds. The technology enables the protein to react with itself to form a tight lock. Most effective when used thinly, the glue is made from the proteins of the streptococcus pyogenes bacteria, enabling it to hook on to human cells.

Even more impressive, the glue can be designed to be selective to what it sticks to. This is essential, as an adhesive this strong would cause havoc if it got stuck to the wrong objects!

⚡ Closing up wounds in seconds
✚ Any previous superglue – and a whole other league to PVA glue
🕒 Here now, but its uses are not fully confirmed

AEROGELS

Solids that are lighter than air

Created by removing liquid from a gel, aerogels are the world's lightest solid materials. High in strength and low in density, they are mesoporous, which means they contain lots of tiny pores, contributing to their low density. There are various types of aerogels, all with different functions and abilities.

First, silica aerogels have an extremely low thermal conductivity and can be used as super-insulators. The most common of the gels, these have even been used on expeditions to Mars.

Carbon aerogels can store high amounts of energy and are ideal as fast-charging super-capacitors. They are predicted to be used as a new type of faster charging and discharging battery in mobile phones and electric cars.

Lastly, metal aerogels combine the properties of the two substances. Being highly conductive and having a high surface area, X-ray optics and hydrogen storage are just two of the possible functions for this hybrid material.

- Protection in firefighter suits
- Surpasses all other heat insulation
- Currently used, but development continues

7X lighter than air

Aerogels are so light a flower or seed head can support them

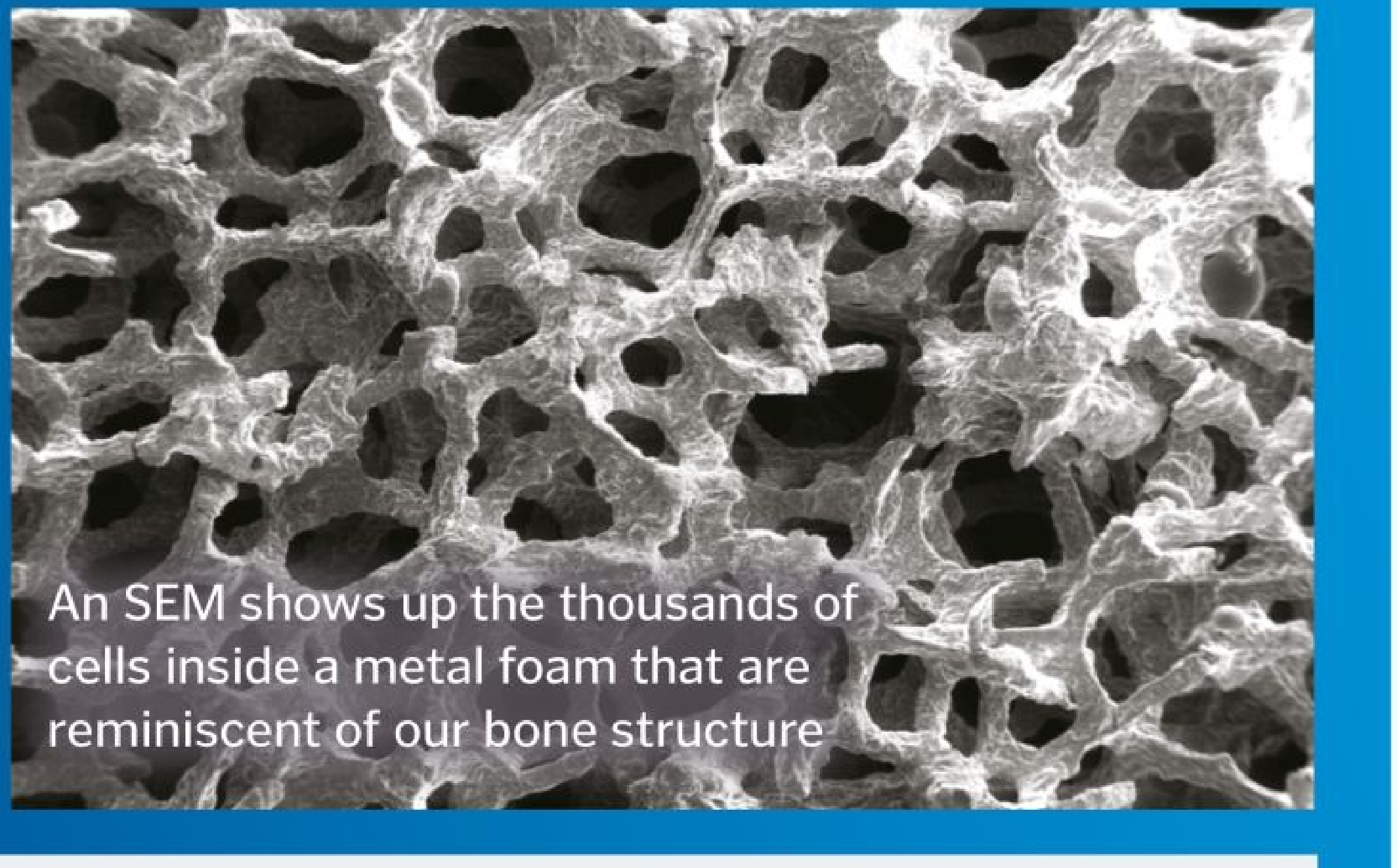
TITANIUMFOAM

The metal that can replace bone

Metal foams are generally solid metals filled with tiny holes, known as 'cells', and up to 95 per cent of their volume can be air. Their biggest selling point is that while they are light and porous, they retain much of their original strength. Made from a mix of metal powder and polyurethane, a binding agent fixes the two substances together under heat.

Titanium foam in particular is tough but at the same time has very similar properties to bone. Experts predict that bone will be able to naturally regrow around it, making this material a very attractive prospect for mending breaks and fractures. Also corrosion-resistant, it can endure nearly all chemicals, making it useful not just as a biocompatible material in the body but also for aerospace components.

- Currently used on drones and lightweight aircraft
- Many metals used in construction
- Expected to be used in bone-reconstruction as soon as research confirms its viability

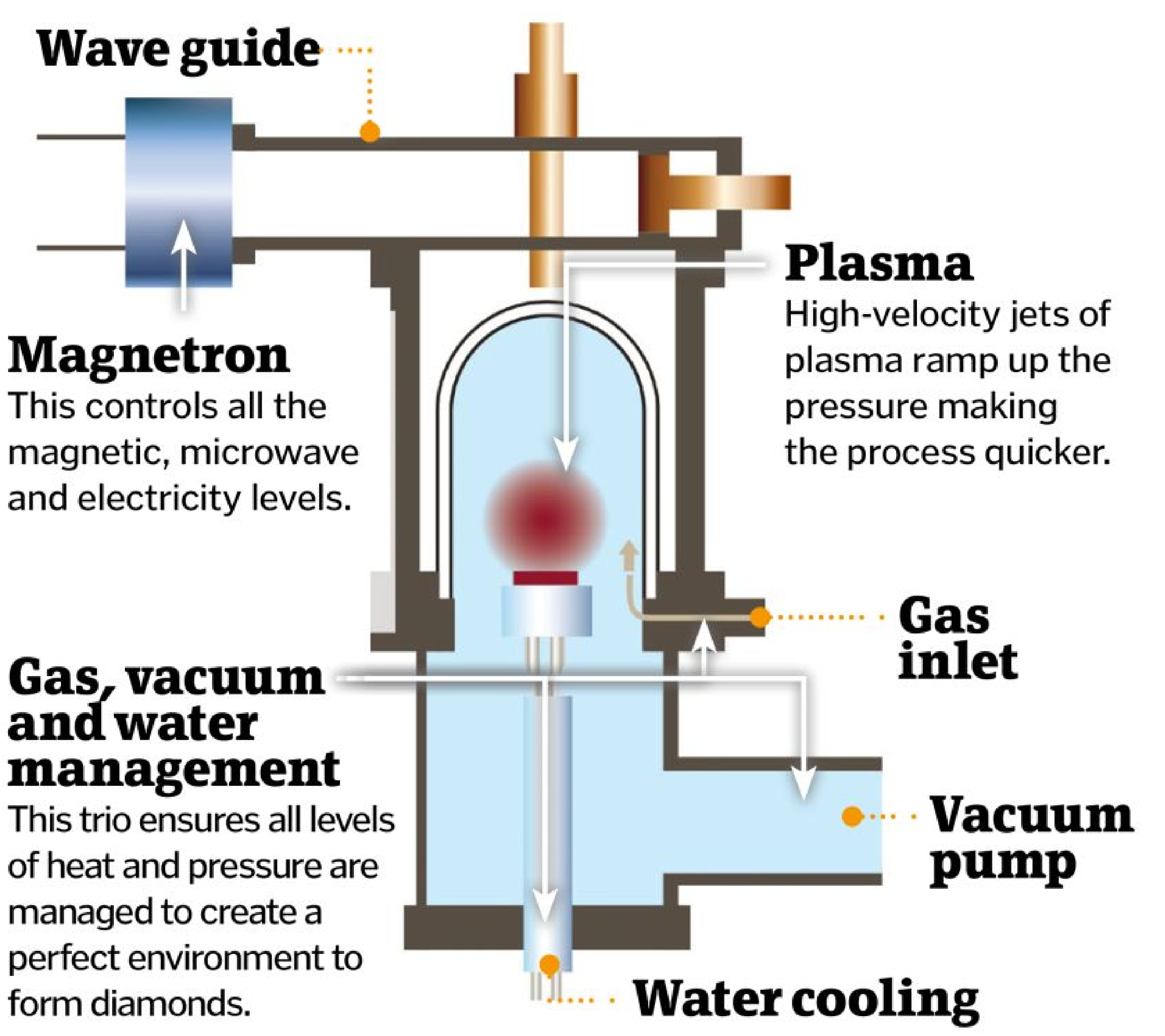


An SEM shows up the thousands of cells inside a metal foam that are reminiscent of our bone structure

> "Titanium is light, strong and, most importantly, corrosion-resistant. The most vital application of titanium foam is as artificial bones, because it can be tailored to have similar mechanical properties to human bones and the porous structure is conducive to ingrowth of tissue cells"
>
> **Yuyuan Zhao, head of the Centre for Materials and Structures, University of Liverpool**

Make your own diamond

Famed for their beauty and toughness in the natural world, diamonds are becoming increasingly rare. Steve Coe, from synthetic diamond manufacturer Element Six, takes us through two ways they're re-creating these gems for drilling, optics, acoustics and more.



Wave guide

Magnetron
This controls all the magnetic, microwave and electricity levels.

Plasma
High-velocity jets of plasma ramp up the pressure making the process quicker.

Gas inlet

Gas, vacuum and water management
This trio ensures all levels of heat and pressure are managed to create a perfect environment to form diamonds.

Vacuum pump

Water cooling

Chemical vapour deposition

Chemical vapour deposition (CVD) uses a hydrocarbon gas mixture, where the diamond is produced in a vacuum system below atmospheric pressure, with carbon atoms supplied from a gas such as methane and deposited in layers onto a substrate.

By passing microwaves through the gas to generate a plasma, at temperatures around 2,000°C (3,632°F), atomic hydrogen is created, enabling impurities in the form of graphite to ensure only the diamond carbon is deposited.

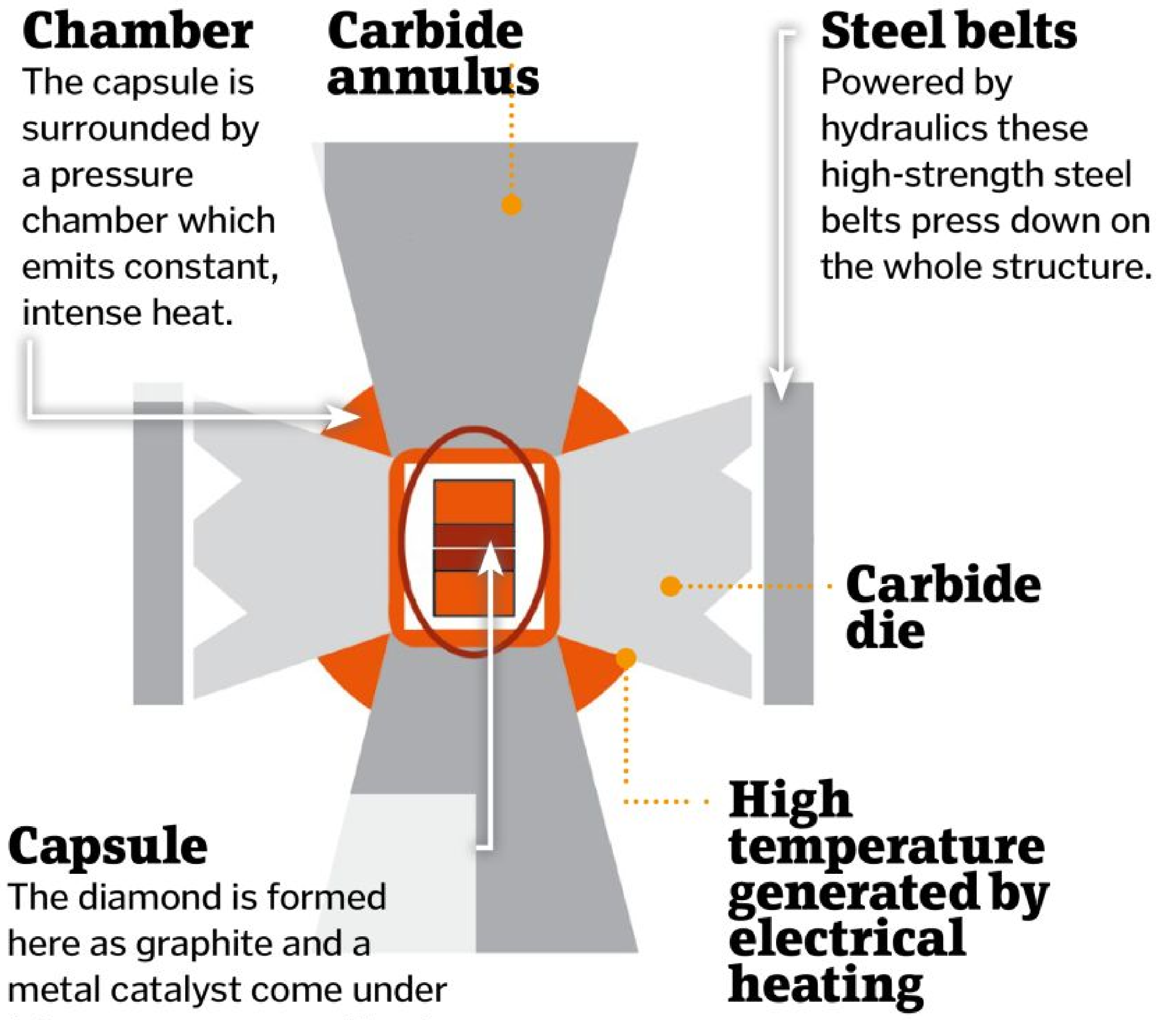
This technique enables tightly controlled growth conditions, eliminating impurities and enabling the engineering of various properties into the diamond material.

High-pressure high-temperature diamond synthesis (HPHT)

This is a synthesis process by which synthetic diamond is created under enormous pressure and temperatures to replicate the Earth's natural process.

The proprietary belt-press technology contains two large anvils to apply hydraulic force to a capsule at the centre.

This capsule contains graphite and a metal catalyst, which react during the process to form diamond. The 15,000 atmospheres of pressure applied to the capsule is the equivalent of taking the Eiffel Tower, inverting it and placing it on a soda can, then turning the temperature up to 1,500°C (2,732°F) – the melting point of steel.



Chamber
The capsule is surrounded by a pressure chamber which emits constant, intense heat.

Carbide annulus

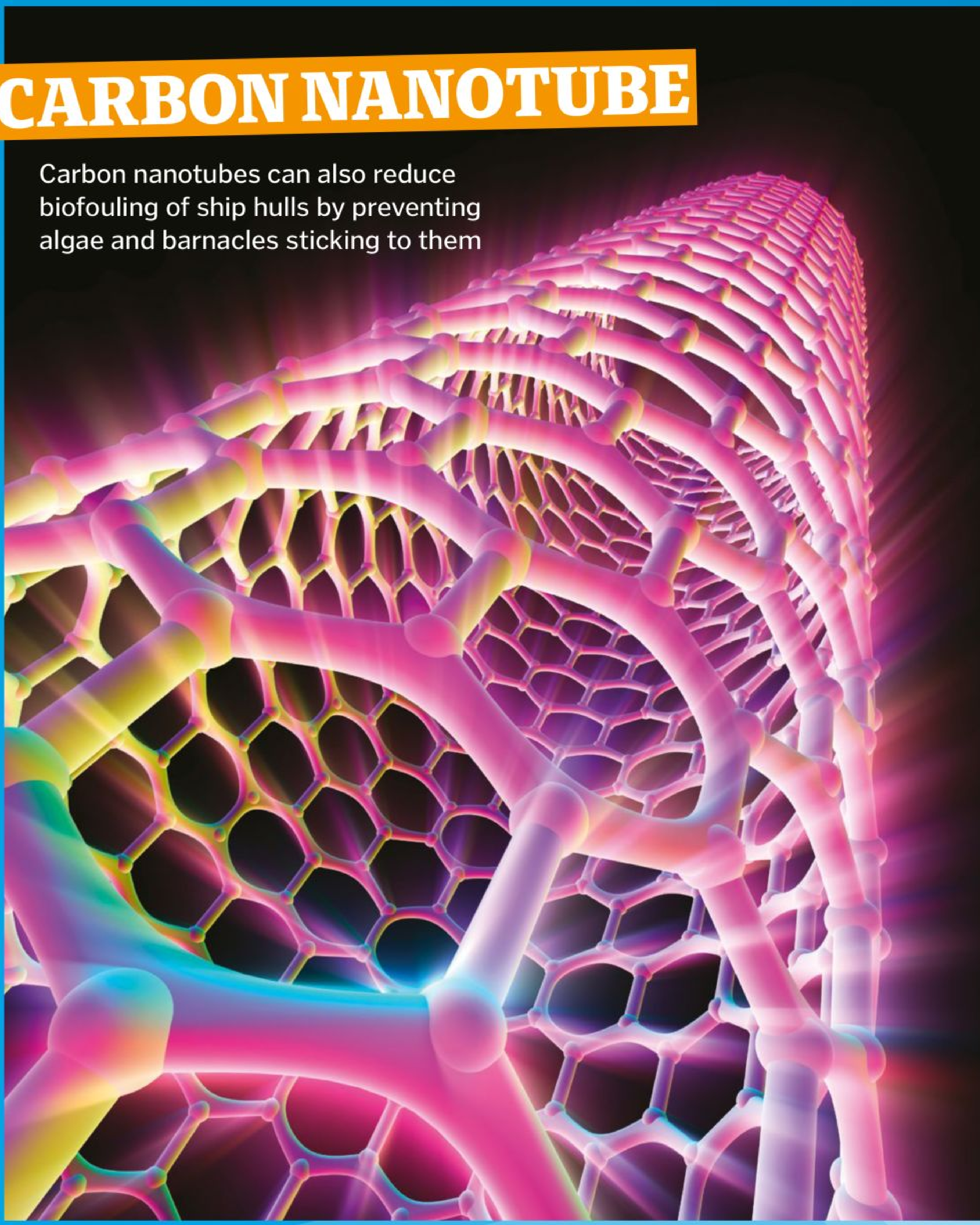
Steel belts
Powered by hydraulics these high-strength steel belts press down on the whole structure.

Carbide die

Capsule
The diamond is formed here as graphite and a metal catalyst come under intense pressure and heat.

High temperature generated by electrical heating

CARBON NANOTUBE



Carbon nanotubes can also reduce biofouling of ship hulls by preventing algae and barnacles sticking to them

Absorbs over 99.5 per cent of light

Carbon nanotubes are said to outperform Kevlar and steel in strength. By having a high specific strength, carbon nanotubes can absorb high impacts by spreading out the force. As well as being strong, the fibre is also ductile and malleable. These characteristics render the material useful as a possible replacement for steel, as well as being applied as synthetic muscles and body or vehicle armour.

If all that wasn't enough, the computing world has also found a use for this super material with its potential to be a long-term replacement for today's silicon computer chips.

Moreover, certain types of carbon nanotube developed by NASA are said to be the darkest material known to man, due to their ability to absorb over 99.5 per cent of photons. This is particularly useful for stopping stray light interfering with sensitive equipment on probes and spacecraft. This property also offers huge potential for more effective solar panels.

⚡ Absorbing multiple wavelengths of light
✚ Silicon transistors in electronic devices
◷ Environmental concerns have stalled its progress so far

800°C

A nanometre of carbon nanotubes is heat resistant enough to withstand lava

"Carbon nanotubes are molecular-scale tubes of graphitic carbon with outstanding properties. They are among the stiffest and strongest fibres known, with a breaking strain around 50 times higher than steel. Carbon nanotubes have an important advantage over graphene, in that they are stiff and strong in compression as well as tension; graphene can't withstand any compression" **Peter Harris, Reading University, and author of *Carbon Nanotube Science***

5 natural inspirations

1 Lotus leaf

When raindrops land on the leaves of the lotus, they cannot settle on the plant. This is down to microscopic bumps over the surface, which increase the contact angle. As the water hits these protrusions, with pockets of air trapped in between, it beads up into spheres and rolls off.

2 Gecko feet

Geckos have the ability to cling to surfaces with adhesive pads called setae on their feet. However, this skill comes undone in wet weather, hence why scientists today are looking to advance on this natural ability by making a waterproof adhesive.

3 Kawazulite

This mineral is a conductor on the outside and an insulator on the inside. It looks set to play a big role in future synthetic insulators.

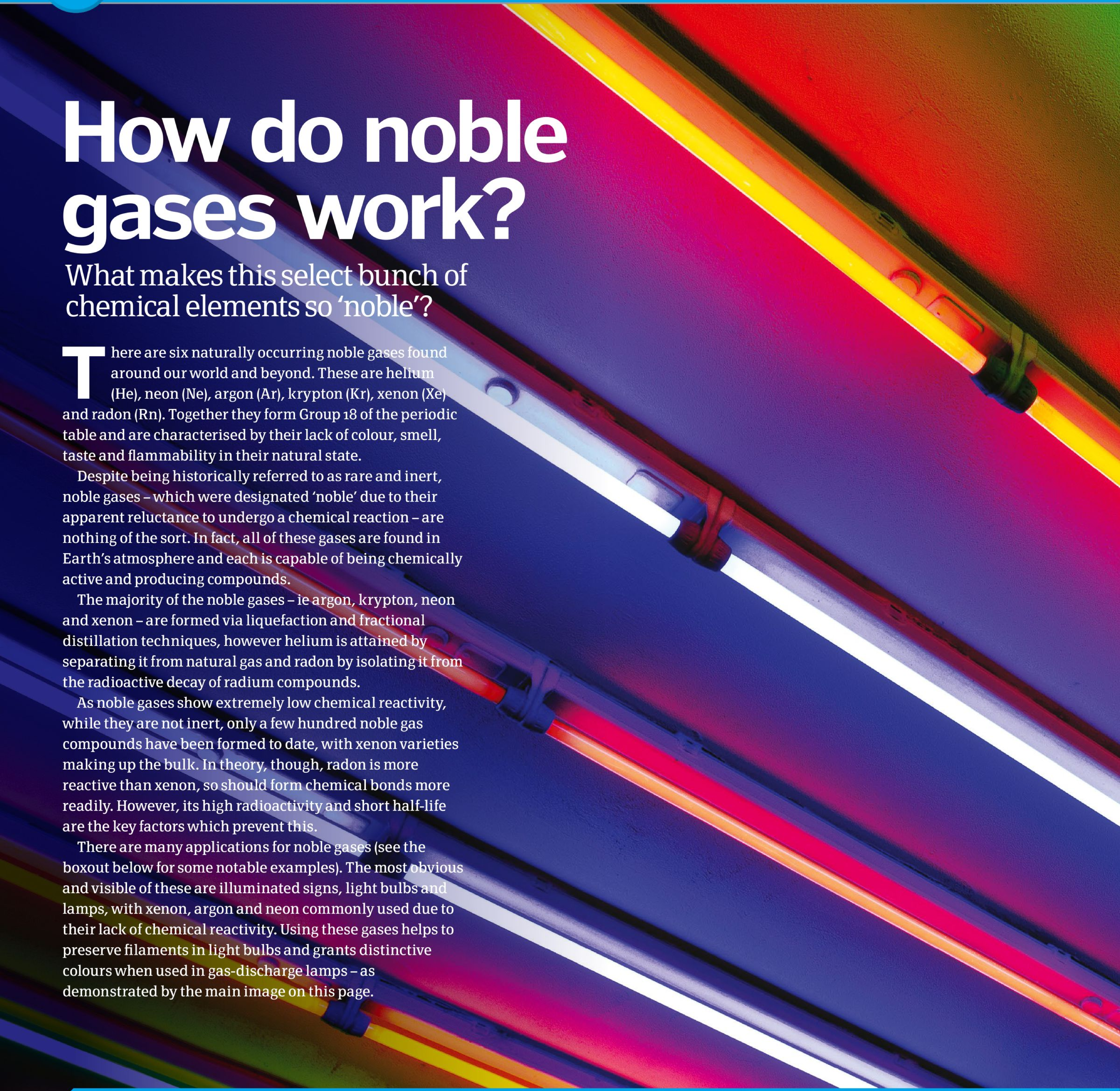
4 Spider silk

Tough and adaptable, spider silk has been used for everything from fish nets to gun crosshairs. Humans have created similar synthetic products such as Kevlar, however these generate a great deal of pollution.

5 Gold nanoparticles

Also called nanogold, these tiny particles are 500 times smaller than the width of a human hair. They have excellent molecular-recognition properties and can detect the proteins on cancer cells by using specialised antibodies.

© Alamy; Corbis; Kikkawa Laboratory; Brad Plummer; Yong Xu; Element Six; SPL; Rex Features



How do noble gases work?

What makes this select bunch of chemical elements so 'noble'?

There are six naturally occurring noble gases found around our world and beyond. These are helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe) and radon (Rn). Together they form Group 18 of the periodic table and are characterised by their lack of colour, smell, taste and flammability in their natural state.

Despite being historically referred to as rare and inert, noble gases – which were designated 'noble' due to their apparent reluctance to undergo a chemical reaction – are nothing of the sort. In fact, all of these gases are found in Earth's atmosphere and each is capable of being chemically active and producing compounds.

The majority of the noble gases – ie argon, krypton, neon and xenon – are formed via liquefaction and fractional distillation techniques, however helium is attained by separating it from natural gas and radon by isolating it from the radioactive decay of radium compounds.

As noble gases show extremely low chemical reactivity, while they are not inert, only a few hundred noble gas compounds have been formed to date, with xenon varieties making up the bulk. In theory, though, radon is more reactive than xenon, so should form chemical bonds more readily. However, its high radioactivity and short half-life are the key factors which prevent this.

There are many applications for noble gases (see the boxout below for some notable examples). The most obvious and visible of these are illuminated signs, light bulbs and lamps, with xenon, argon and neon commonly used due to their lack of chemical reactivity. Using these gases helps to preserve filaments in light bulbs and grants distinctive colours when used in gas-discharge lamps – as demonstrated by the main image on this page.

Where are noble gases used?

Arc lamps

A specialised type of gas-discharge lamp, arc lights pass electricity through a bulb full of ionised gas, such as xenon or argon. They're used in IMAX cinemas among other places.

Blimps

Today, most blimps are filled with helium due to its lightness and incombustibility. Hydrogen was used originally but was phased out due to its high flammability.

MRI scanners

One of the most advanced pieces of medical equipment, magnetic resonance imaging scanners use liquid helium to cool the superconducting magnets inside.

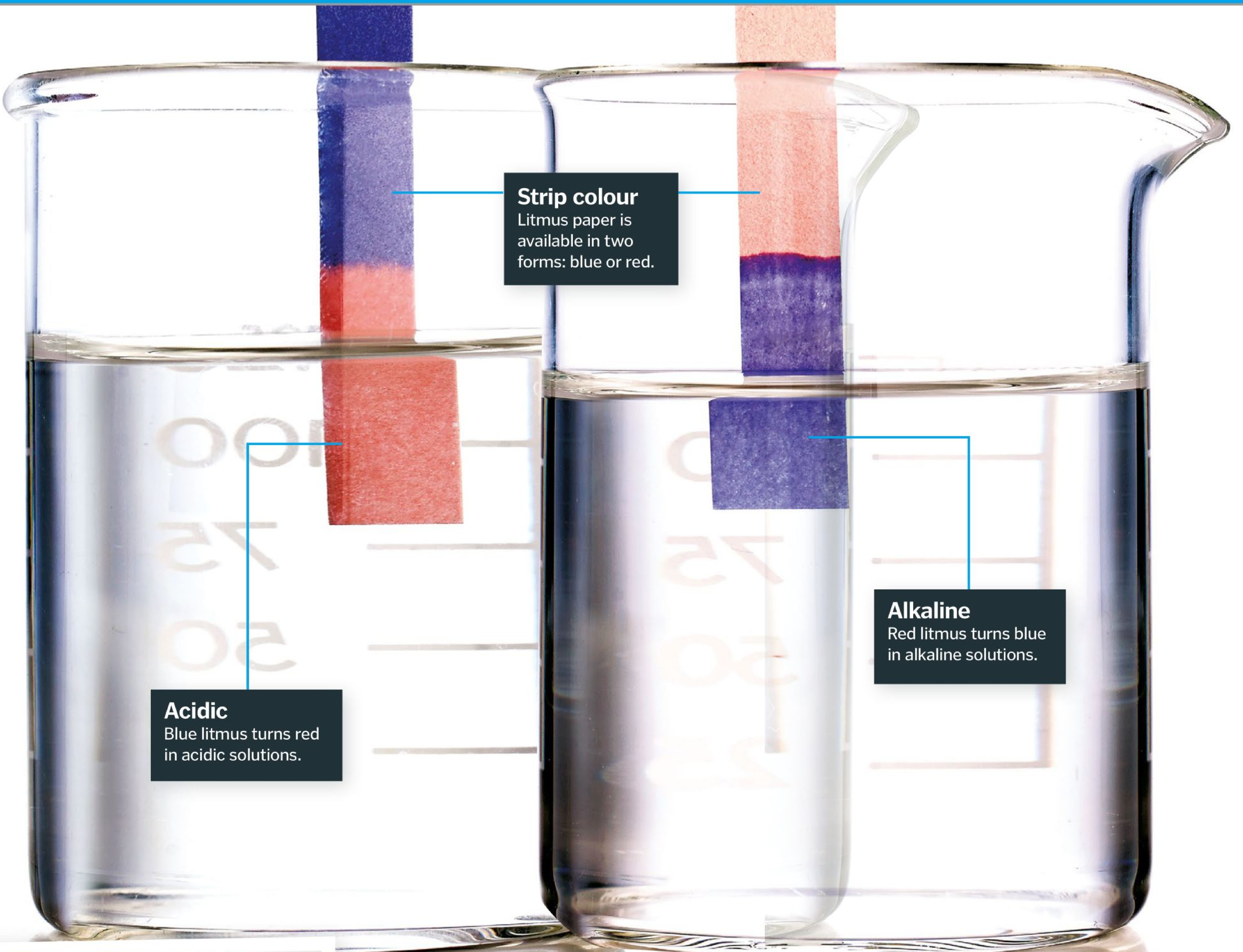
> "As noble gases show extremely low reactivity only a few hundred noble gas compounds have been formed"

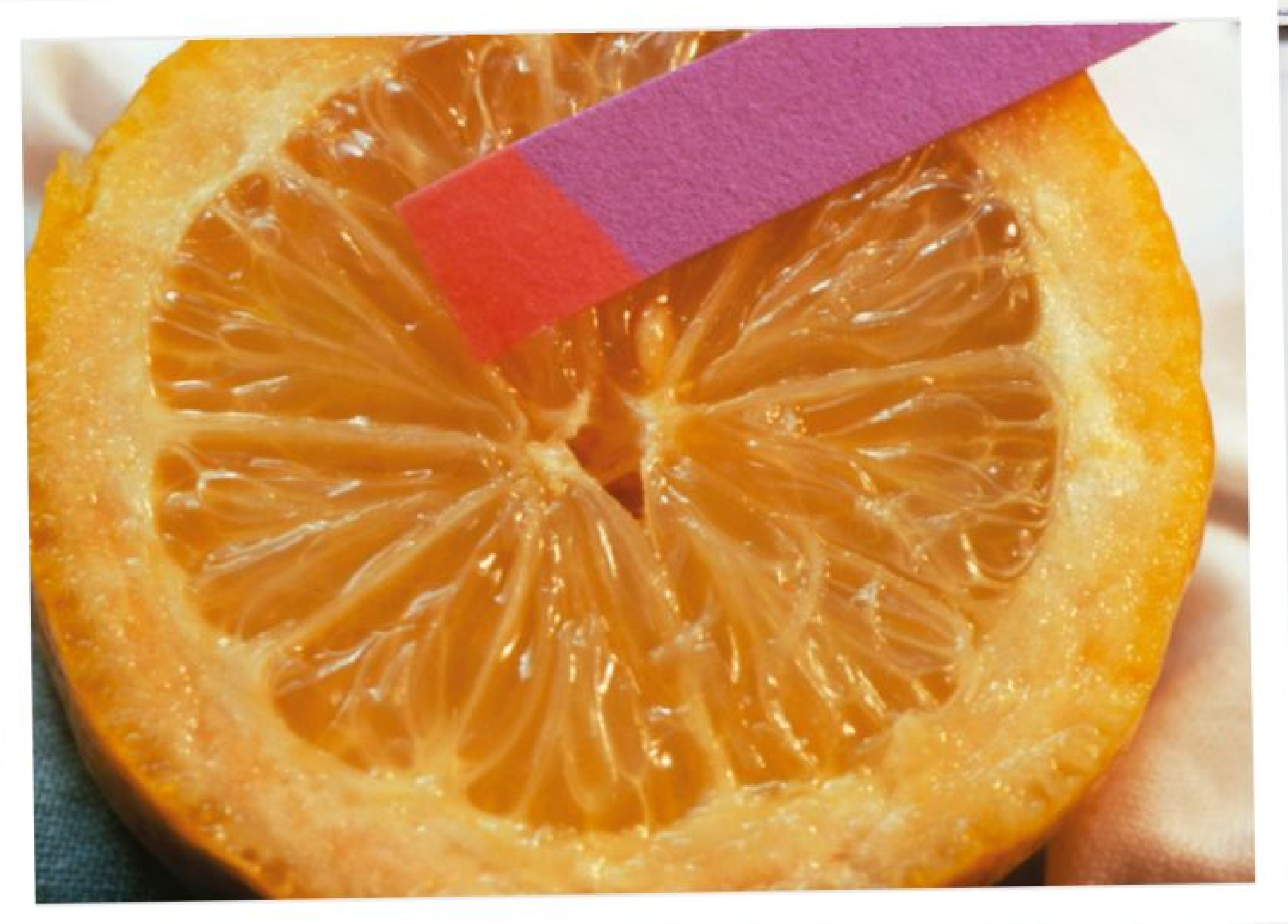
Illuminated signs
Many illuminated signs and billboards utilise noble gases due to their ability to generate vibrant colours when ionised – neon lights being a prime example.

Refrigerants
Due to their incredibly low boiling points – for instance, argon boils at -186 degrees Celsius (-302.8 degrees Fahrenheit) – the Group 18 gases are often used in cryogenics.

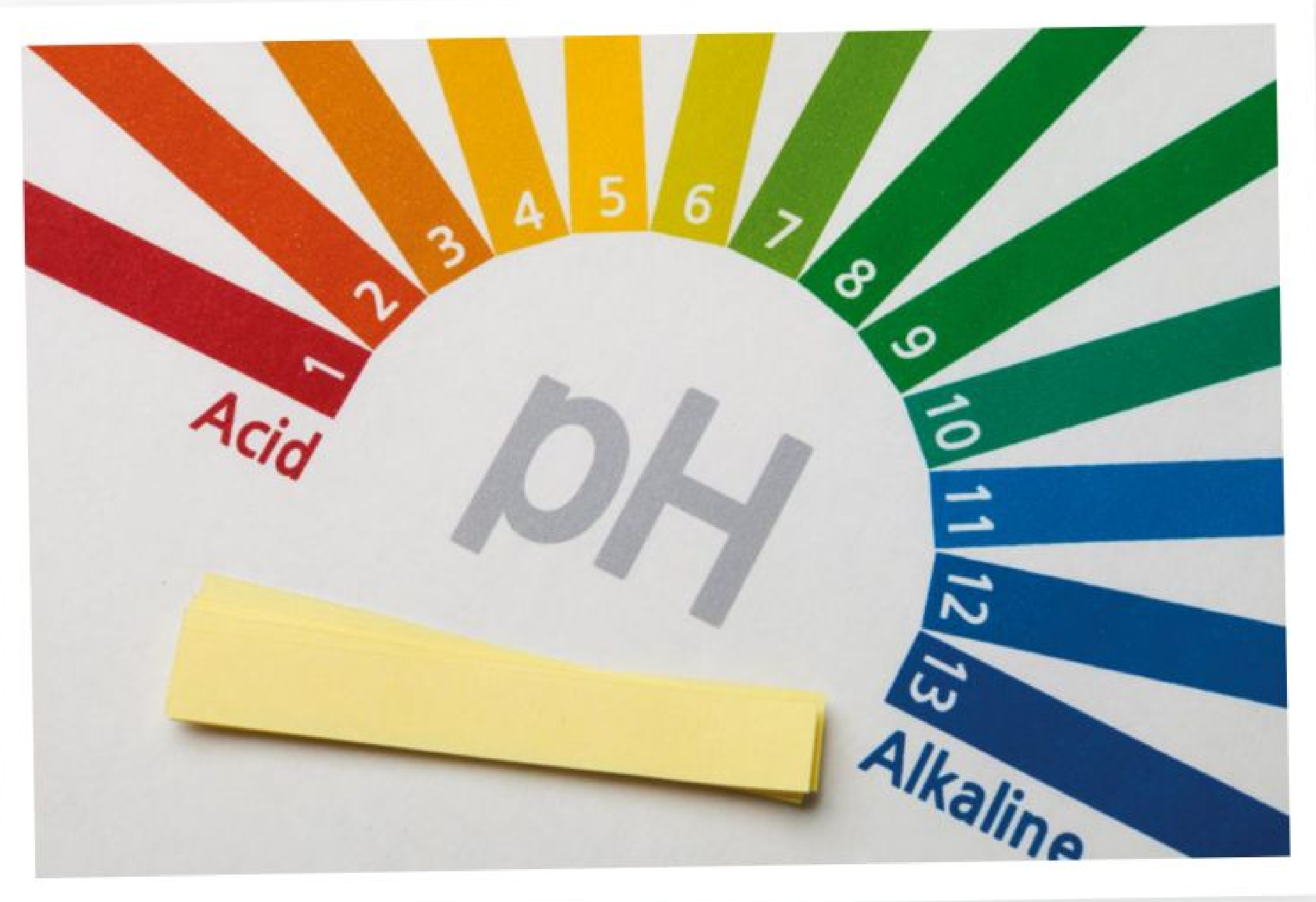
Radiotherapy
Despite the noble gas radon being highly radioactive and able to cause cancer, it can also be used as part of radiotherapy treatments to control or kill malignant cells.

© Atlant; Getty; Thinkstock


Strip colour
Litmus paper is available in two forms: blue or red.
Acidic
Blue litmus turns red in acidic solutions.
Alkaline
Red litmus turns blue in alkaline solutions.



In this image, blue litmus paper turns red in the presence of citric acid found on citrus fruits



Not to be confused with litmus, universal indicator can also detect pH, but is able to show exactly how acidic, alkaline or neutral a solution is

How litmus paper reveals pH

The science behind the simple tool able to identify a solution's acidity

Most young chemists will be familiar with litmus paper from science lessons, and older chemists for assessing their home brew. This helpful tool is used to determine the acidity or alkalinity of a solution through a simple colour change, where acidic solutions turn the paper red, and alkaline (basic) solutions turn the paper blue. This provides a visual indication of the pH, which is a measure of the concentration of hydrogen ions in a solution.

Water molecules can be broken down into positively charged hydrogen ions and negatively charged hydroxide ions. Acidic solutions have higher concentrations of hydrogen ions than hydroxide ions, while the opposite is true of basic solutions. In water and other neutral solutions, the concentration of hydrogen and hydroxide ions is equal.

The colour-changing properties of the paper are due to crushed and fermented lichen that has been dried onto the surface. Lichens are a diverse group of organisms, many of which possess large, light-absorbing molecules called chromophores. These absorb differing wavelengths of light depending on their atomic structure, which can be altered by the presence of the ions found in acidic and basic solutions.

Wavelengths at the blue end of the visible spectrum are absorbed when the chromophores react with hydrogen atoms, and wavelengths at the red end of the spectrum are absorbed when the chromophores react with hydroxide ions present in bases.

Depending on which wavelengths of light are absorbed, the paper will appear a different colour. We can then use this colour to determine if the solution is acidic or basic.

© SPL

How glow sticks work

They're used by partygoers, campers, divers and other outdoor adventurers, but what makes a glow stick glow?

The colour of a glow stick depends on the colour of the dye that's inserted

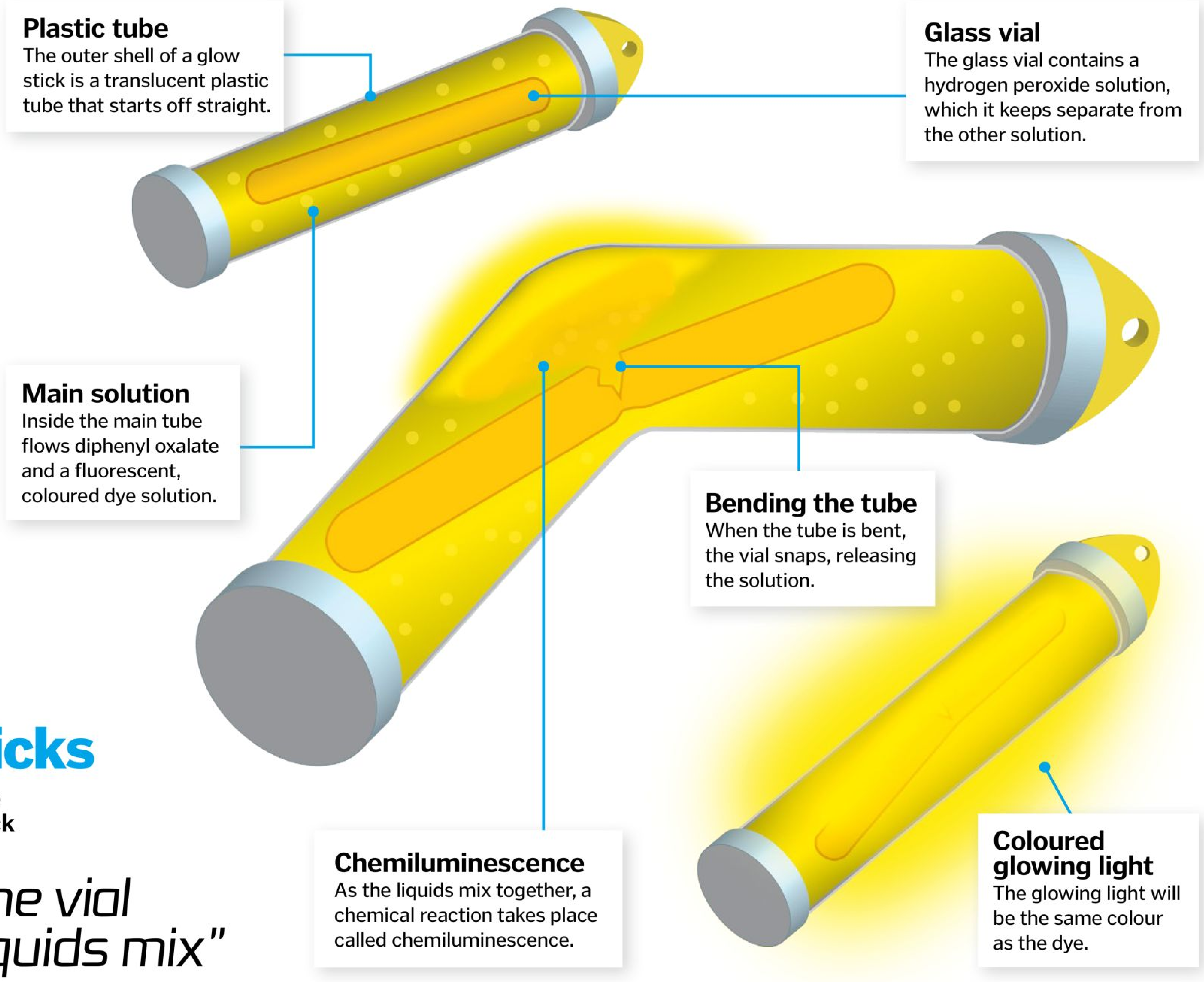
A glow stick is a translucent plastic tube that contains two liquids: hydrogen peroxide and diphenyl oxalate. The latter is also mixed with a fluorescent dye. The diphenyl oxalate and dye solution flow freely in the glow stick, whereas the hydrogen peroxide solution is contained in a fine, glass vial within the tube. When the stick bends, the vial breaks and the liquids mix together.

A chemical reaction then occurs, known as chemiluminescence, which results in a glowing light. This happens as the electrons in the dye rise to a higher energy level, become excited, and then release coloured light as they fall back down.

The science behind glow sticks

See how chemistry plays a vital role in putting the glow in your glow stick

> *"When it bends, the vial breaks and the liquids mix"*



Plastic tube
The outer shell of a glow stick is a translucent plastic tube that starts off straight.

Glass vial
The glass vial contains a hydrogen peroxide solution, which it keeps separate from the other solution.

Main solution
Inside the main tube flows diphenyl oxalate and a fluorescent, coloured dye solution.

Bending the tube
When the tube is bent, the vial snaps, releasing the solution.

Chemiluminescence
As the liquids mix together, a chemical reaction takes place called chemiluminescence.

Coloured glowing light
The glowing light will be the same colour as the dye.

Why glitter is so sticky

Discover what glitter is made from and why it sticks to almost everything

Although craft glitter used to be made from different types of metals, these days cosmetic and craft glitter are both made of plastic composed of polymer molecules. The materials are produced on thin sheets, and the shine comes from a coating of reflective metal, like aluminium foil. Colour is applied before the sheets are treated and then cut into tiny pieces using a special machine.

The material glitter is made from, along with its small size, both contribute to its stickiness. Since plastic easily picks up electrons, it's likely that static electricity occurs when glitter comes into contact with dry surfaces.

Experts state that the viscosity of air might also play a part in glitter's stickiness. Since a glitter particle is flat, when it rests on a smooth object it pushes out the air from beneath it, and the air on top of the glitter particle pushes it down. Unless air is somehow let under it to enable it to rise, the glitter will remain relatively stationary.

Another theory is that glitter gets its stickiness from van der Waals forces, the weak electronic interactions that occur between electrically neutral molecules.

It's believed that machinist Henry Ruschmann invented glitter in 1934

© Thinkstock; Illustration by Adam Markiewicz

TOXIC SCIENCE

Discover some of the deadliest substances known to humankind

Toxic substances include anything that can physically harm us after we inhale, swallow or touch it, from an innocent bee sting to full-blown cyanide poisoning. Defining toxicity is tricky since almost anything is poisonous at high enough doses – even water. Acute poisoning follows just one exposure, for example, nibbling a death cap mushroom, but chronic exposure – like inhaling cigarette smoke over decades – can be equally, if not more, damaging.

Toxins are toxic substances produced by living organisms. They use toxins mainly to ward off predators or paralyse prey. Small but deadly bacteria produce some of the most potent toxins known, including botulinum toxin A (Botox). Other toxic substances occur naturally on Earth, such as the hydrogen sulphide produced by volcanic eruptions. We humans have even invented man-made ones for use as pesticides, insecticides (eg DDT) or chemical weapons (eg sarin, VX).

Targeting different parts of the body, toxic substances can damage us in an alarming number of ways. Neurotoxins are some of the most effective, affecting the brain and nervous system and causing muscles to freeze or twitch uncontrollably. Other substances can burst our red blood cells or cause allergic reactions.

But not everyone is affected by toxic substances in the same way. How toxic a chemical is depends on how easily it is absorbed, metabolised and eventually expelled by the body. Children are generally more vulnerable as their bodies are not able to get rid of toxic substances as effectively. Different species are also more or less susceptible to various poisons – for example, it takes 1,000 times more dioxin to kill a hamster than a guinea pig.

Key

Toxicity: 1 – Unlikely to kill / 5 – Super-deadly
Rarity: 1 – Very common / 5 – Very rare

Botulinum toxin A (Botox)

This is the most toxic substance in nature: just one gram (0.04 ounces) could kill 14,000 people if swallowed – or 8.3 million if injected! Produced by Clostridium botulinum bacteria, this neurotoxin is responsible for botulism, a rare but life-threatening illness transmitted principally through contaminated canned food. Botulinum disrupts communication between nerves and muscle cells, gradually paralysing its victims and finally leading to respiratory failure. Extremely small doses of botulinum toxin can, however, be used to treat muscle spasms and excessive sweating and to paralyse the muscles that cause wrinkles (sold commercially as Botox).

The statistics…

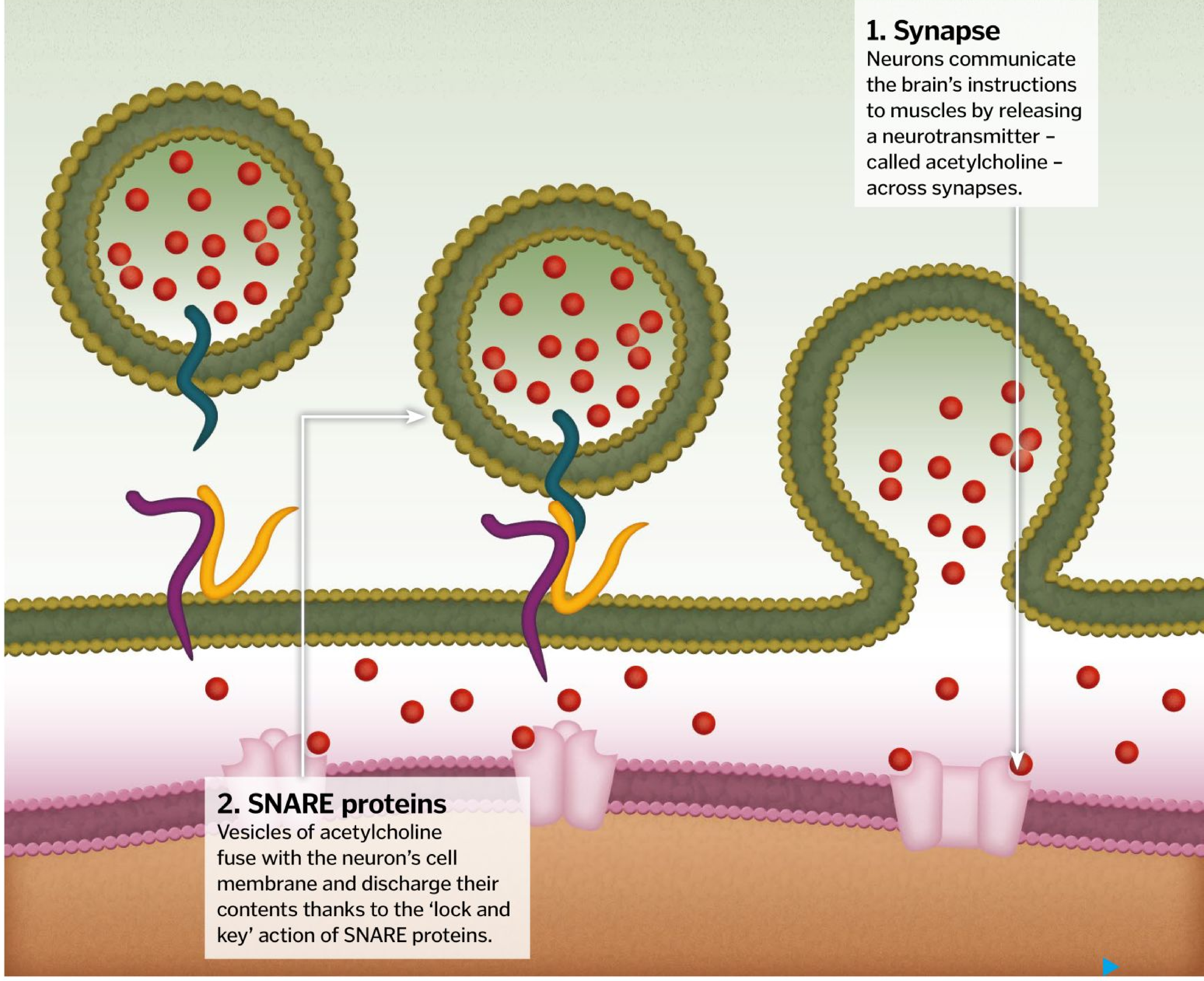
Main symptoms: Double vision, droopy eyelids, difficulty swallowing, slurred speech, muscle weakness, paralysis

Antidote: Horse-derived antitoxin

Time to death: Rarely fatal when treated

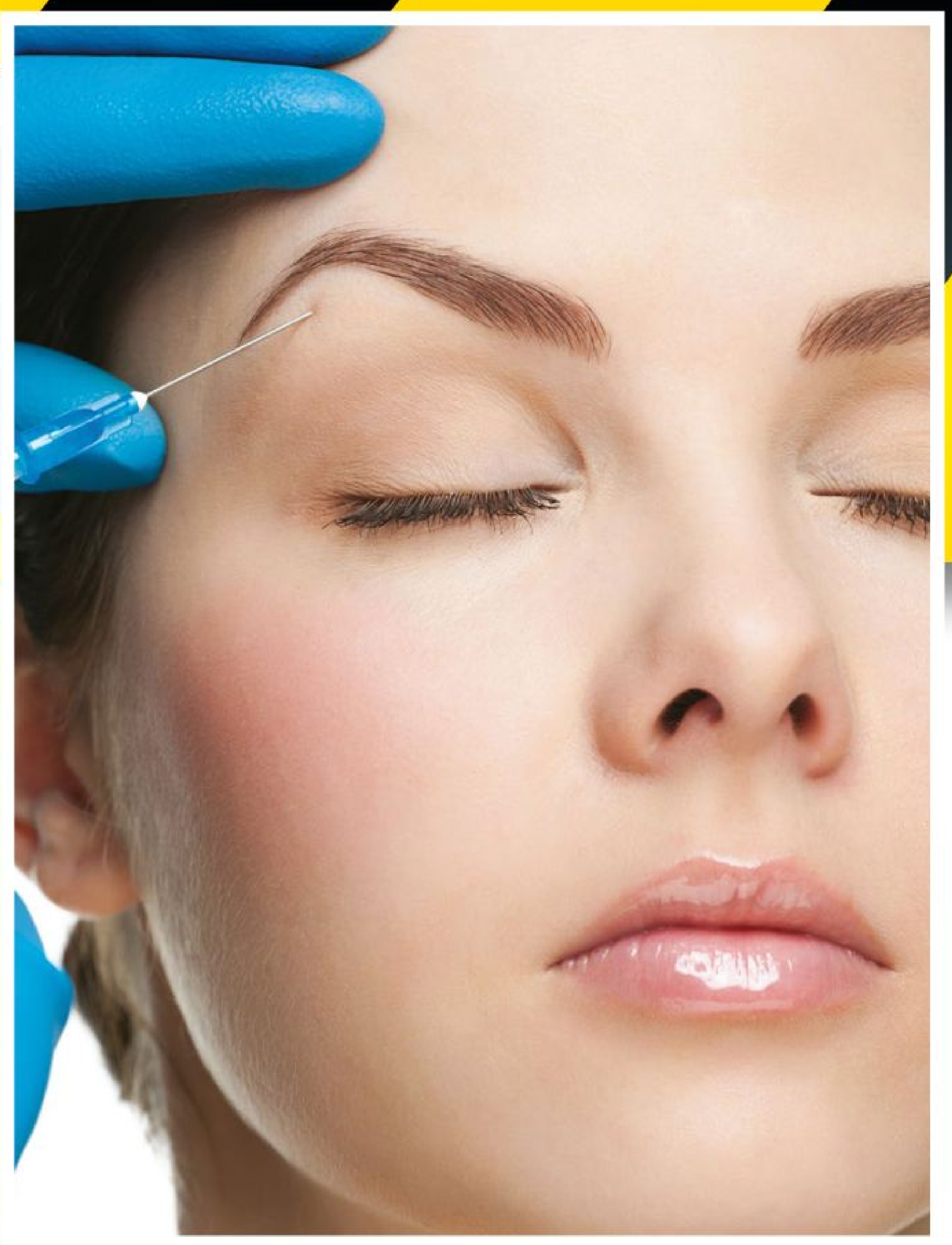
Toxicity rating: 5

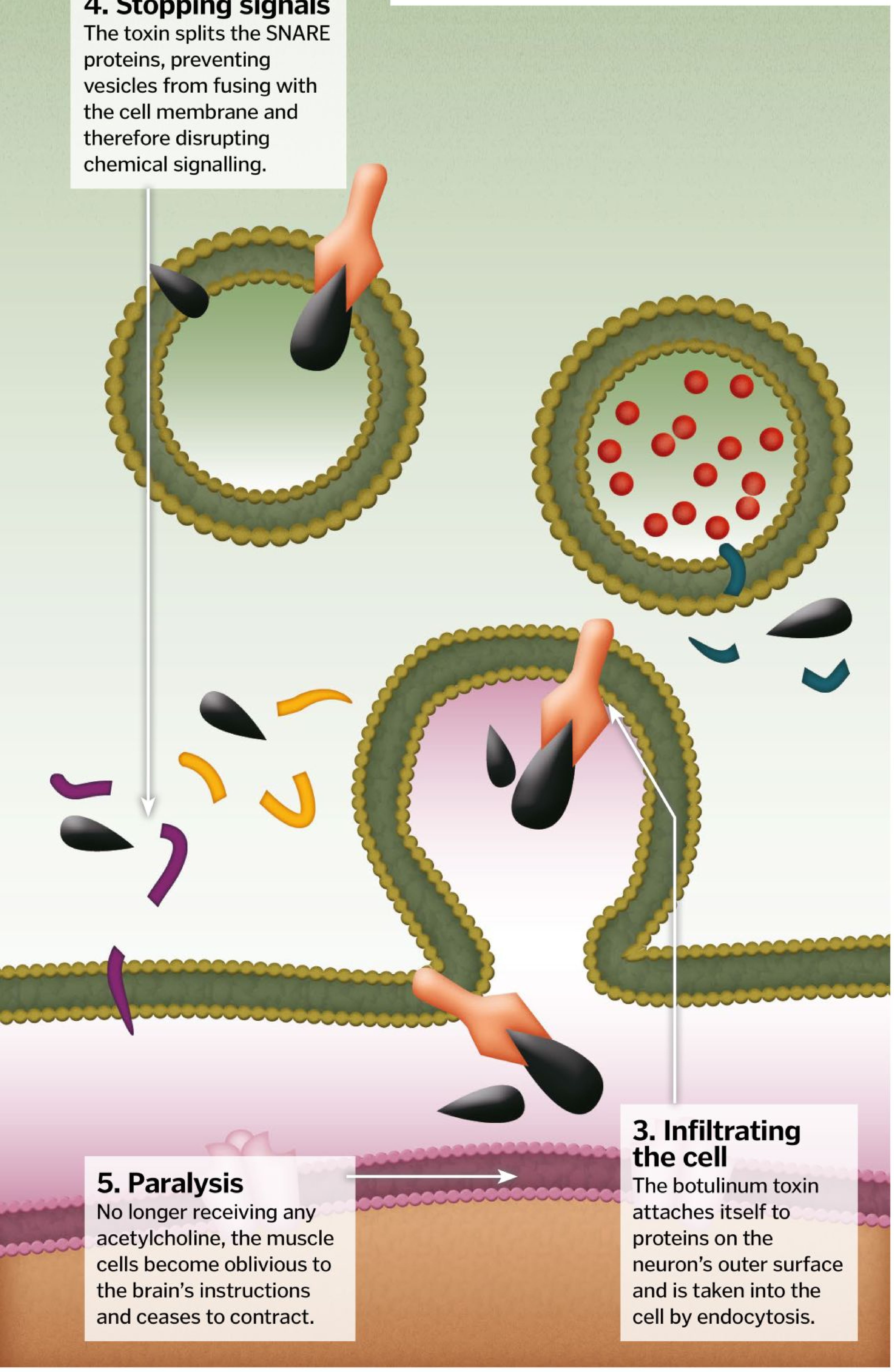
Rarity rating: 4



1. Synapse
Neurons communicate the brain's instructions to muscles by releasing a neurotransmitter – called acetylcholine – across synapses.

2. SNARE proteins
Vesicles of acetylcholine fuse with the neuron's cell membrane and discharge their contents thanks to the 'lock and key' action of SNARE proteins.





3. Infiltrating the cell
The botulinum toxin attaches itself to proteins on the neuron's outer surface and is taken into the cell by endocytosis.

4. Stopping signals
The toxin splits the SNARE proteins, preventing vesicles from fusing with the cell membrane and therefore disrupting chemical signalling.

5. Paralysis
No longer receiving any acetylcholine, the muscle cells become oblivious to the brain's instructions and ceases to contract.

Asbestos

Asbestos is the name given to a handful of different minerals which share one common feature: bunches of fibrous crystals. Boasting an array of insulating properties topped off with a low price tag, asbestos was a popular building material until its toxic effects came to light. With repeated inhalation, asbestos fibres accumulate in the lungs, causing deadly diseases like asbestosis, an inflammatory lung condition, and cancer. These diseases typically don't develop until 15-30 years after exposure. Although now banned in most countries, older buildings can still release the harmful crystals when demolished.

The statistics...

Main symptoms: Shortness of breath, coughing, chest pain

Antidote: No current cure for asbestosis, but relief treatment

Time to death: Various

Toxicity rating: 4

Rarity rating: 3

Ricin

Found in the castor oil plant, ricin is a toxic protein that wreaks havoc on ribosomes, the cell's protein builders. The result is severe damage to major organs. Just one milligram of ricin is enough to kill an adult if inhaled or ingested, leading many countries to investigate its use as a biological weapon. The castor oil plant's popularity as an ornamental shrub and the relative ease of extracting the toxin from castor beans have also made ricin the poison of choice for many assassins.

The statistics...

Main symptoms: Diarrhoea, nausea, accelerated heart beat, hypotension, seizures

Antidote: The UK military has developed an antidote, but it remains to be tested on humans

Time to death: 2–5 days

Toxicity rating: 5

Rarity rating: 2

Carbon monoxide

Colourless and odourless, carbon monoxide gas has a knack for going unnoticed. It is produced by the incomplete combustion of organic fuels including gas, coal and wood – occurring, for example, when inadequate ventilation deprives a gas-burning stove of oxygen. As a result, carbon monoxide poisoning is the most common type of air poisoning around the home. Carbon monoxide molecules bind tightly to haemoglobin, the oxygen-carrying protein in blood. Taking oxygen's place, they prevent blood from delivering oxygen to cells. You can reduce the risk by keeping your home well ventilated and servicing appliances such as boilers every year.

The statistics...

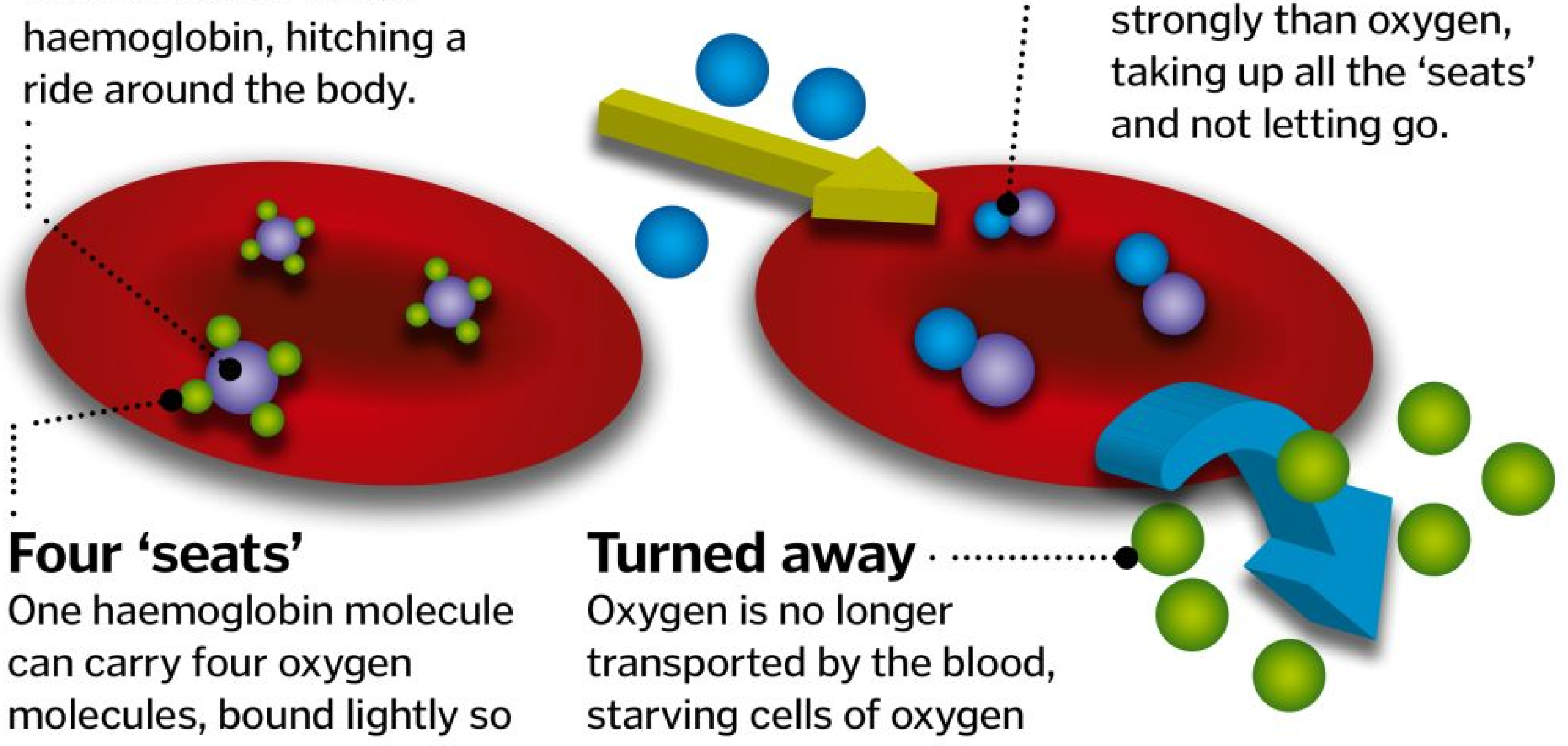
Main symptoms: Headache, nausea, vomiting, dizziness, fatigue, weakness, loss of consciousness

Antidote: Oxygen

Time to death: 2-3 minutes in acute cases

Toxicity rating: 4

Rarity rating: 1



Haemoglobin
Oxygen binds with the iron atoms inside haemoglobin, hitching a ride around the body.

Carbon monoxide
Carbon monoxide binds to iron 200 times more strongly than oxygen, taking up all the 'seats' and not letting go.

Four 'seats'
One haemoglobin molecule can carry four oxygen molecules, bound lightly so they are easily released.

Turned away
Oxygen is no longer transported by the blood, starving cells of oxygen and eventually killing them.

Although toxicity varies across species, there can be enough tetrodotoxin in a single pufferfish to kill 30 people

Tetrodotoxin

Thrill-seeking Japanese diners are sometimes tempted to try fugu, a variety of pufferfish. The catch? If the chef slips up, they risk being poisoned with tetrodotoxin, a potent neurotoxin contained in the fish's gonads, liver, intestines and skin. Opening nerves' ion channels, tetrodotoxin acts similarly to batrachotoxin to block nerve impulses, causing paralysis and death by respiratory failure. Although chefs need a licence to serve fugu, mishaps still poison an estimated 200 people each year, with half of them dying. Pufferfish are not the only ones to use tetrodotoxin; it is one of the most common toxins in the marine world, employed by scores of fish, crabs and molluscs, including the blue-ringed octopus.

The statistics...

Main symptoms: Numbness of the lips and tongue, followed by paralysis that spreads to the entire body, heart failure

Antidote: None known

Time to death: 4-6 hours

Toxicity rating: 4

Rarity rating: 4

Toxic household

Keep an eye on the toxic substances lurking in your home...

Phthalates

Personal care products, and also vinyl flooring, can contain phthalates – substances linked to changes in hormone levels and liver cancer.

Medicines

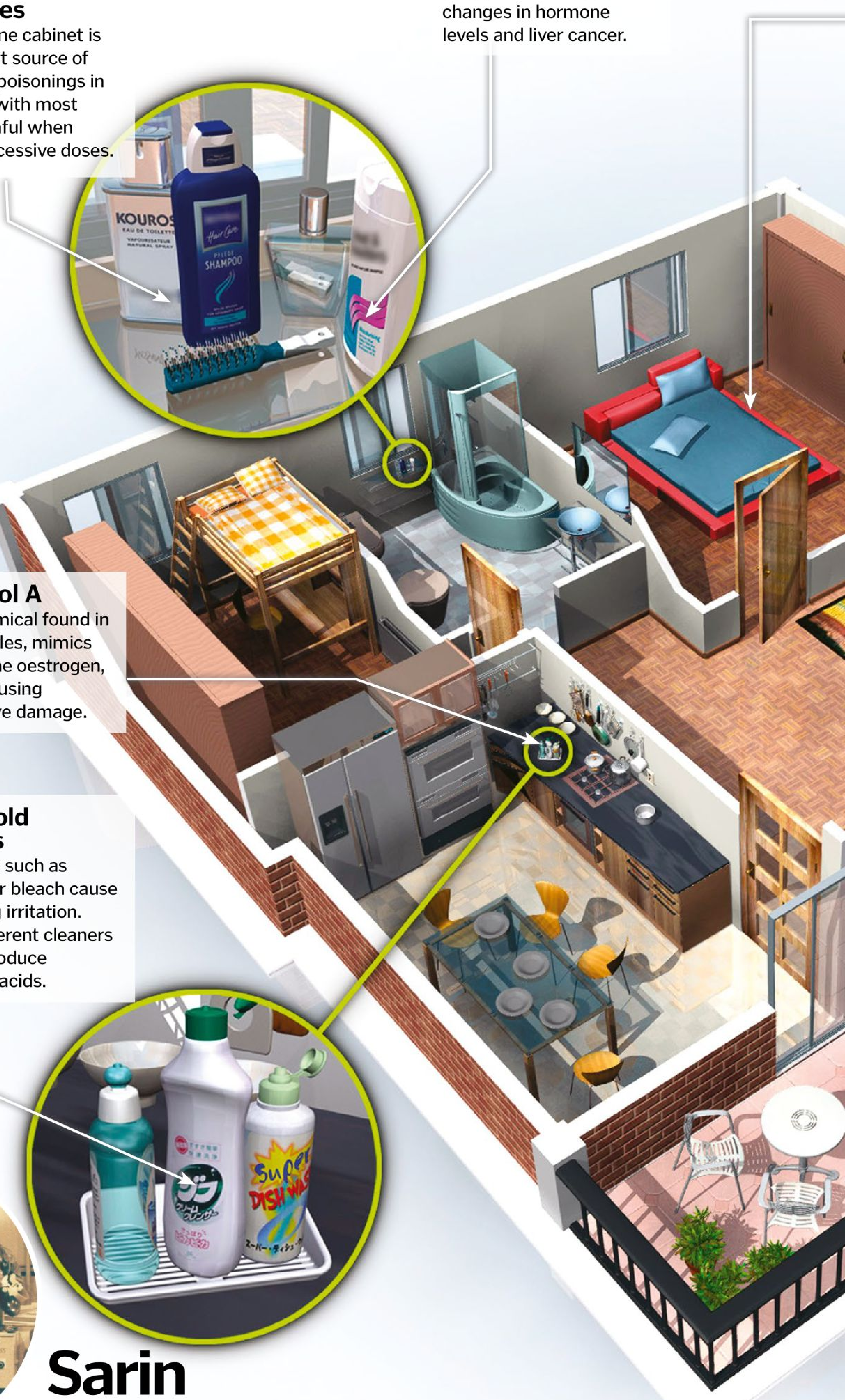
The medicine cabinet is the greatest source of accidental poisonings in the home, with most drugs harmful when taken in excessive doses.

Bisphenol A

BPA, a chemical found in plastic bottles, mimics the hormone oestrogen, possibly causing reproductive damage.

Household cleaners

Ingredients such as ammonia or bleach cause skin or lung irritation. Mixing different cleaners can also produce dangerous acids.



Cyanide

Whether inhaled or ingested, cyanide is one of the fastest-acting poisons known, sealing death sentences in minutes. Chemically speaking, a cyanide is a compound with a triple bond between a carbon and a nitrogen atom. Hydrogen cyanide gas and solid sodium or potassium cyanide are highly toxic, preventing the body's cells from using oxygen and starving the heart and the brain. Certain fruit pits contain cyanide and small quantities of hydrogen cyanide are present in engine exhaust fumes. Industrial uses include gold mining and pesticides – one of which was used by the Nazis in gas chambers.

The statistics...

Main symptoms: Nausea, rapid breathing, dizziness, headache, convulsions – leading to death

Antidote: In smaller doses hydroxocobalamin is one known antidote, but generally fatal

Time to death: As little as a minute

Toxicity rating: 5

Rarity rating: 2

The statistics...

Main symptoms: Constriction of pupils, drooling, difficulty breathing, loss of control over bodily functions, convulsions

Antidote: Atropine

Time to death: 15 minutes to a few hours

Toxicity rating: 5

Rarity rating: 5

Sarin

Sarin is a man-made nerve agent, first developed as a pesticide by German scientists in 1938. A colourless, tasteless but extremely volatile gas, it works by inhibiting the body's enzyme which breaks down the neurotransmitter acetylcholine, causing it to accumulate at nerve endings. This signals to muscles to contract uncontrollably, triggering a range of unpleasant effects which culminate in death by asphyxiation. Like all chemical weapons, sarin is outlawed and has been used only a handful of times: like during the Iran-Iraq War in the Eighties, and in terrorist attacks on the Tokyo subway in 1995.

Flame retardants
PBDEs (polybrominated diphenyl ethers) found in mattresses and furniture to make them fireproof may cause learning and memory deficits.

VOCs
Just after fitting, the glues and dyes used in new flooring can emit harmful volatile organic compounds (VOCs).

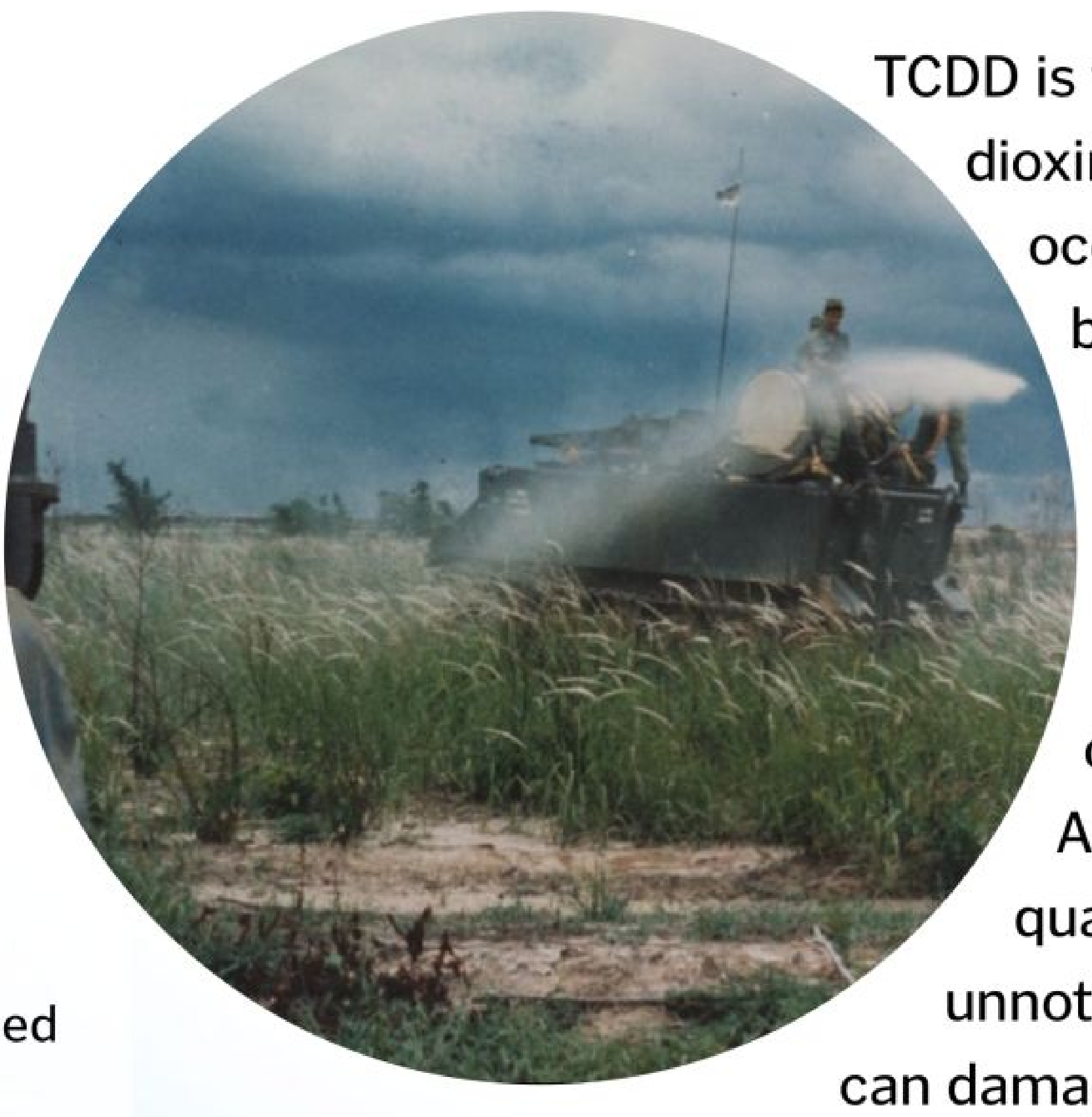
Carbon monoxide
Gas-burning fires can produce potentially deadly carbon monoxide gas if they don't receive enough ventilation.

Lead paint
Houses built before 1978 may contain neurotoxic lead-based paint which can be exposed if it peels.

Cigarettes
Smokers inhale over 700 poisons with each drag, including arsenic, benzene, cadmium, hydrogen cyanide, carbon monoxide and even radioactive polonium-210.

Garden chemicals
Exposure to pesticides, herbicides and fertilisers has been linked to asthma as well as various neurological, developmental and immunological disorders.

TCDD



TCDD is the deadliest of the dioxins. These chemicals occur in the natural world but are produced in much larger quantities by industry. Dioxins persist for a long time, accumulating in the fat cells of living organisms. As a result, small quantities of dioxins may go unnoticed, but over time they can damage the immune and reproductive systems and increase the likelihood of diabetes and cancer. High doses such as those experienced during the Vietnam War with the USA's use of Agent Orange – a herbicide contaminated with TCDD – spark an immediate reaction. They are also thought to cause cancer and birth defects years later, although TCDD's effect on the body is not yet fully understood.

The statistics...

Main symptoms: Skin disease (chloracne) and discolouration, lung infection; in the longer term: cancer, birth defects

Antidote: None

Time to death: Unconfirmed

Toxicity rating: 4

Rarity rating: 2

Batrachotoxin

Batrachotoxin is the deadliest ingredient in a lethal cocktail of toxins secreted by certain poison-dart frogs. Native tribes use it as a weapon, dipping their blowgun dart tips in the frogs' toxins – these darts kill prey almost instantaneously. The frogs don't actually produce batrachotoxin themselves but obtain it by eating poisonous beetles. Batrachotoxin opens nerve cells' ion channels permanently, preventing them from creating an electric potential. This blocks cell signalling, paralysing muscles. Heart muscles are particularly sensitive to the toxin, leading to an irregular pulse and, soon after, a heart attack.

The statistics...

Main symptoms: Convulsions, salivation, muscle contractions

Antidote: None

Time to death: Under 10 minutes

Toxicity rating: 5

Rarity rating: 4

Digitalis

Digitalis, or foxglove, owes its toxicity to cardiac to the glycosides digitoxin and digoxin – compounds with the capacity to help and harm. When ingested, glycosides affect the behaviour of heart muscles. In controlled doses, they can regulate the heart beat and treat congestive heart failure. But taking too much digitalis medication, or eating those parts of the plant, can trigger a fatal heart attack; that said, eating foxgloves usually induces vomiting which can prevent an overdose. US serial killer Charles Cullen poisoned at least 29 elderly patients in nursing homes by administering overdoses of insulin and digoxin.

The statistics...

Main symptoms: Nausea, vomiting, diarrhoea, visual disturbances, hallucinations, reduced heart rate

Antidote: Digoxin Immune Fab: this binds to the toxin, preventing it from acting on the body

Time to death: Rarely fatal but can kill in 24 hours

Toxicity rating: 3

Rarity rating: 2

Worst of the rest

1 Alpha-amanitin

This deadly toxin is taken up by the liver, where it inhibits an enzyme needed for cell division, causing liver failure.

Found in: Death cap and destroying angel mushrooms

2 Arsenic

Once believed to have killed Napoleon (now disproved), arsenic disrupts cells' energy transport, leading to organ failure.

Found in: Wood-preserving chemicals, insecticides

3 VX

VX is the most toxic nerve agent ever synthesised – ten times more toxic than sarin.

Found in: Russia and the USA – but now being destroyed

4 Strychnine

This poison causes some gruesome symptoms such as muscle convulsions, arching of the body and facial spasms.

Found in: Strychnos trees, rodent pesticides

5 Polonium-210

If ingested, this radioactive material bombards the body with deadly alpha particles.

Found in: Certain rocks, can settle on broad-leaf plants

© SPL; Thinkstock; Bjoertvedt

Acids and bases

Discover the differences between acids and bases, and find out why they act the way they do

It is widely known that lemons taste sour due to their acid content, soil needs the optimum pH level for plants to grow properly and acid rain can wipe out entire ecosystems. But what really makes one thing acidic and the other one basic (alkaline)? Why can they be so corrosive? And why does litmus paper turn different colours when dipped in acid or a base?

Acids and bases can be defined in terms of their concentration of hydrogen ions. Normally an atom of hydrogen consists of one proton and one electron giving it a balanced electrical charge – protons being positively charged and electrons being negatively charged. Take away the electron and you are left with an ion of hydrogen, or a single proton, or 'H+', as it is often written. The thing about ions is they are very reactive, as they no longer have a balanced charge. They are constantly seeking ions of the opposite charge – an atom or molecule with an unequal number of electrons than protons, with which to react.

A strong acid has a high concentration of H+ ions and is defined by its ability to 'donate' hydrogen ions to a solution, whereas a base, also know as an alkali, has a much lower concentration of H+ ions and is defined by its ability to 'accept' hydrogen ions in a solution. Therefore, acids mixed with bases become less acidic and bases mixed with acids become less basic, or less alkaline.

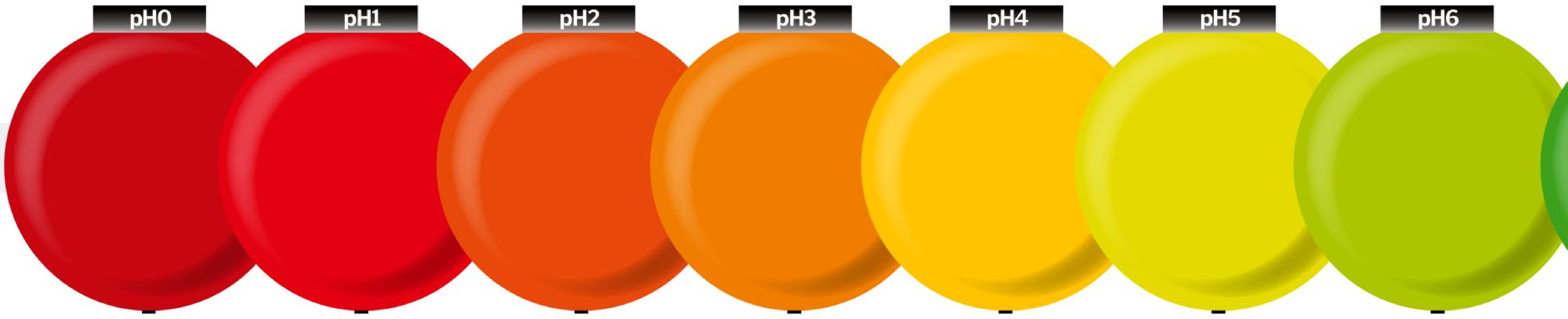
Certain concentrated bases can attack living tissue and cause severe burns due to the ions reacting with the skin. However, the process of bases reacting with the skin, and other materials, is different to that of acids. That's why we call some concentrated acids 'corrosive', and reactive concentrated bases are 'caustic'.

Acids and bases have many uses, but stronger ones can be harmful

"A strong acid has a high concentration of H+ ions"

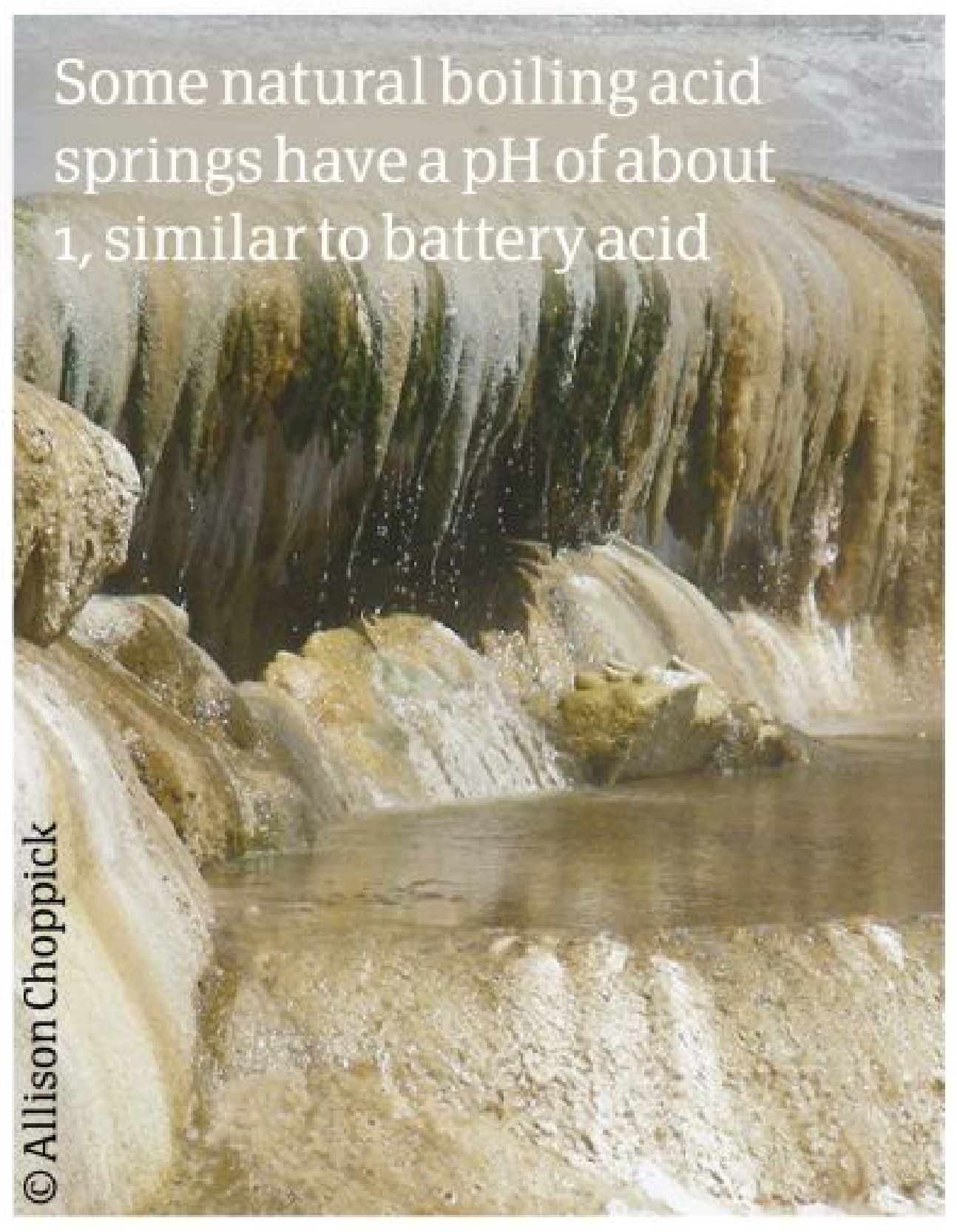
The power of hydrogen

The letters pH stand for 'power of hydrogen', as the scale refers to the concentration of hydrogen (H+) ions in the solution. It measures the acidity or basicity of a solution, with pH values ranging from 0-14, 0 being really acidic and 14 being really basic. A substance in the middle of the scale with a pH of 7 is classed as neutral, as it contains equal numbers of oppositely charged ions.



Acid

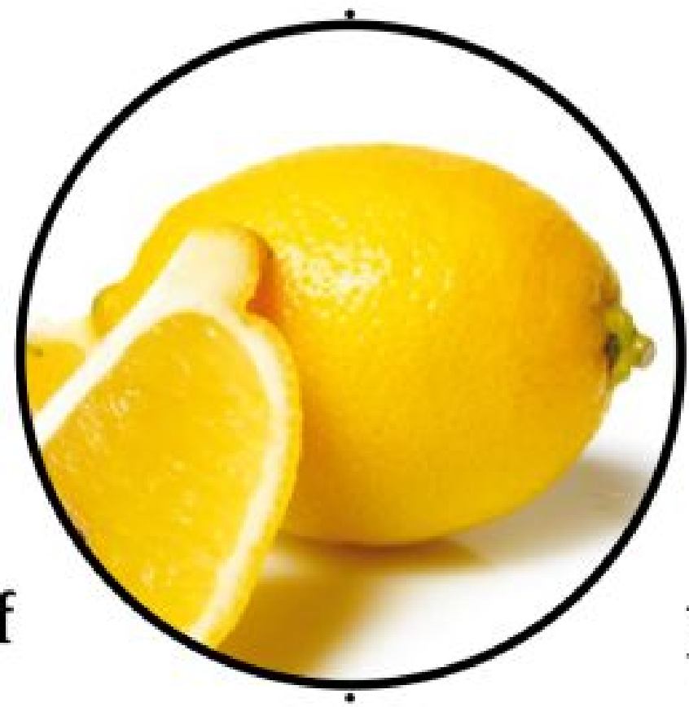
A compound which 'donates' hydrogen ions when placed in an aqueous solution. The higher the concentration of hydrogen ions released, the stronger the acid.


Some natural boiling acid springs have a pH of about 1, similar to battery acid

© Allison Choppick

Hydrofluoric acid
A highly corrosive substance which as a gas is a severe poison and acts a catalyst in oil refining.

Suphuric acid
Used in the production of fertilisers, this strong acid is a chemical found in acid rain.



Lemon juice
Lemon juice is about 5% citric acid – a weak organic acid that gives lemons their sour taste.

Cola
Cola contains phosphoric acid, which has been linked to the lowering of bone density in various studies.

Beer
Various acids are formed during the fermentation process in beer production. The addition of CO_2 also causes the pH to lower slightly.

Black coffee
Levels of acids found in coffee can be affected by the altitude at which the coffee was grown and the minerals present in the soil.

Cow's milk
Milk goes sour over time due to the bacteria producing lactic acid as part of a fermentation process.

The litmus test

We can test the acidity or alkalinity of a substance using litmus paper. Litmus paper is that which has been treated with a mixture of 10-15 natural dyes obtained from lichens. The dyes work as indicators, whereby upon exposure to acids (a pH less than 7) the paper turns red and upon exposure to bases (a pH more than 7) the paper turns blue. When the pH is neutral (pH equal to 7), the dyes cause the paper to turn purple.

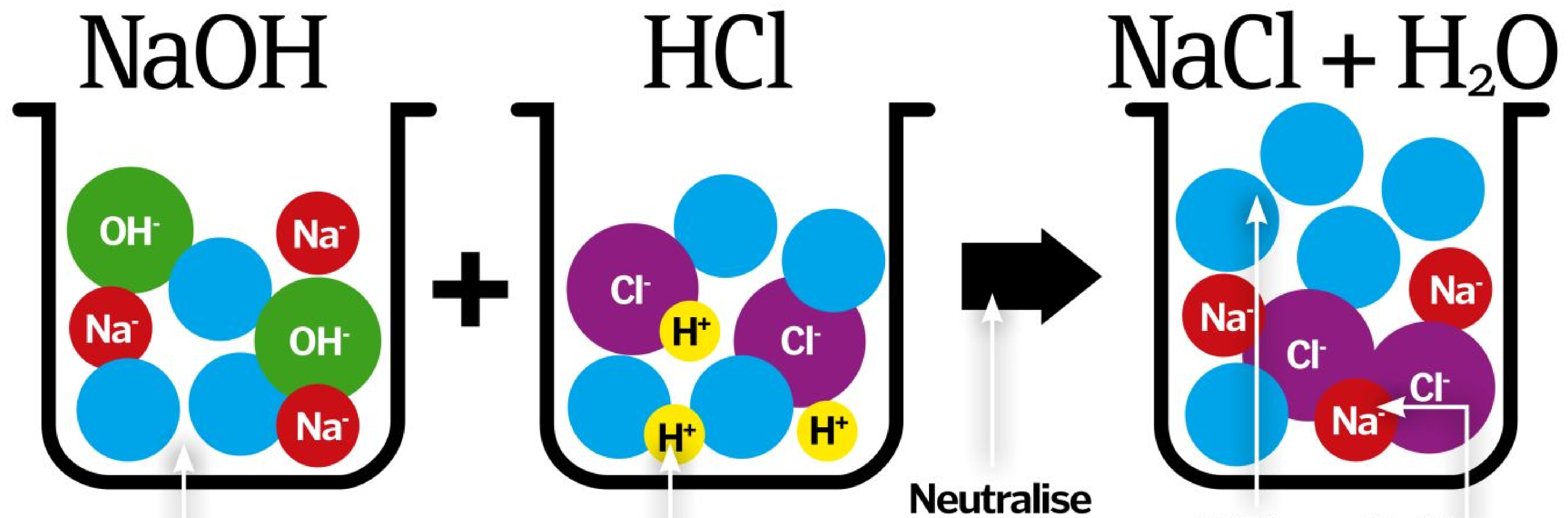
Red cabbage juice can also be used to distinguish between acids and bases, as it contains a natural pH indicator called 'flavin'. Upon exposure to acid, flavin turns a red colour, neutral solutions appear a purple colour and the basic solutions result in a greenish-yellow colour.

Neutralisation

A neutralisation reaction is the combination of an acid and base that results in a salt and, usually, water. In strong bases and acids, neutralisation is the result of the exchange of hydrogen and hydroxide ions, H+ and H- respectively, which produces water. With weak acids and bases, neutralisation is simply the transfer of protons from an acid to a base. The production of water, with a neutral pH of 7, indicates the neutralisation of the acid and base, while the resultant salt will often have a pH that is also neutral.

Neutralisation has a variety of practical uses. For example, as most plants grow best at neutral pH7, acidic or alkaline soil can be treated with chemicals to change its pH. In the case of acidic soil this is often calcium carbonate (chalk) or calcium oxide (quicklime). Another example is the human stomach, which contains hydrochloric acid. However, too much can lead to indigestion, so the acid can be neutralised with a base such as an indigestion tablet.

How do an acid and base react to produce salt, water and heat?



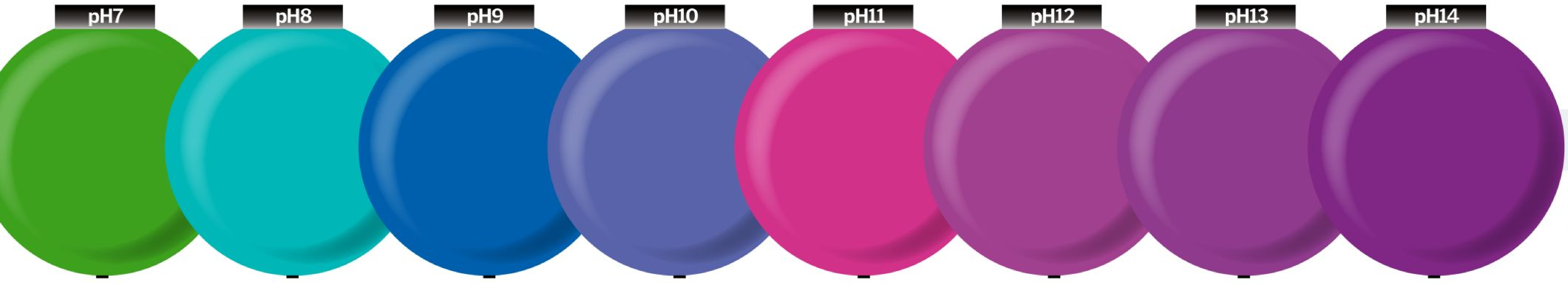
Sodium hydroxide
This strong alkali (a base soluble in water) has a pH of 13 or 14.

Hydrochloric acid
With a pH of 1 or 2, the H+ ions of this strong acid are removed by the alkali.

Neutralise
By removing the H+ ions, the alkali neutralises the acid and turns the ions into water.

Water
Neutral water of pH7 is produced.

NaCl
Neutral sodium chloride, or table salt, is also produced.



Distilled water
Pure water is neutral as it contains the same amount of positive ions as negative ions, though most water isn't pure in this sense.

Baking soda
A slightly salty substance used as a base in foods to regulate the pH if something is too acidic.

Toothpaste
Acidic toothpaste can put enamel at risk of decay, so a weak base such as sodium hydroxide is added in order to regulate the pH.

Milk of magnesia
A weak base of magnesium hydroxide in water, used to ease stomach aches caused by too much acid.

Ammonia solution
When placed in water, ammonia removes protons from a small fraction of the water to form ammonium and hydroxide. It is used in many cleaning products for its basic properties.

Bleach
Can contain sodium hypochlorite at different strengths, making it a strong caustic base.

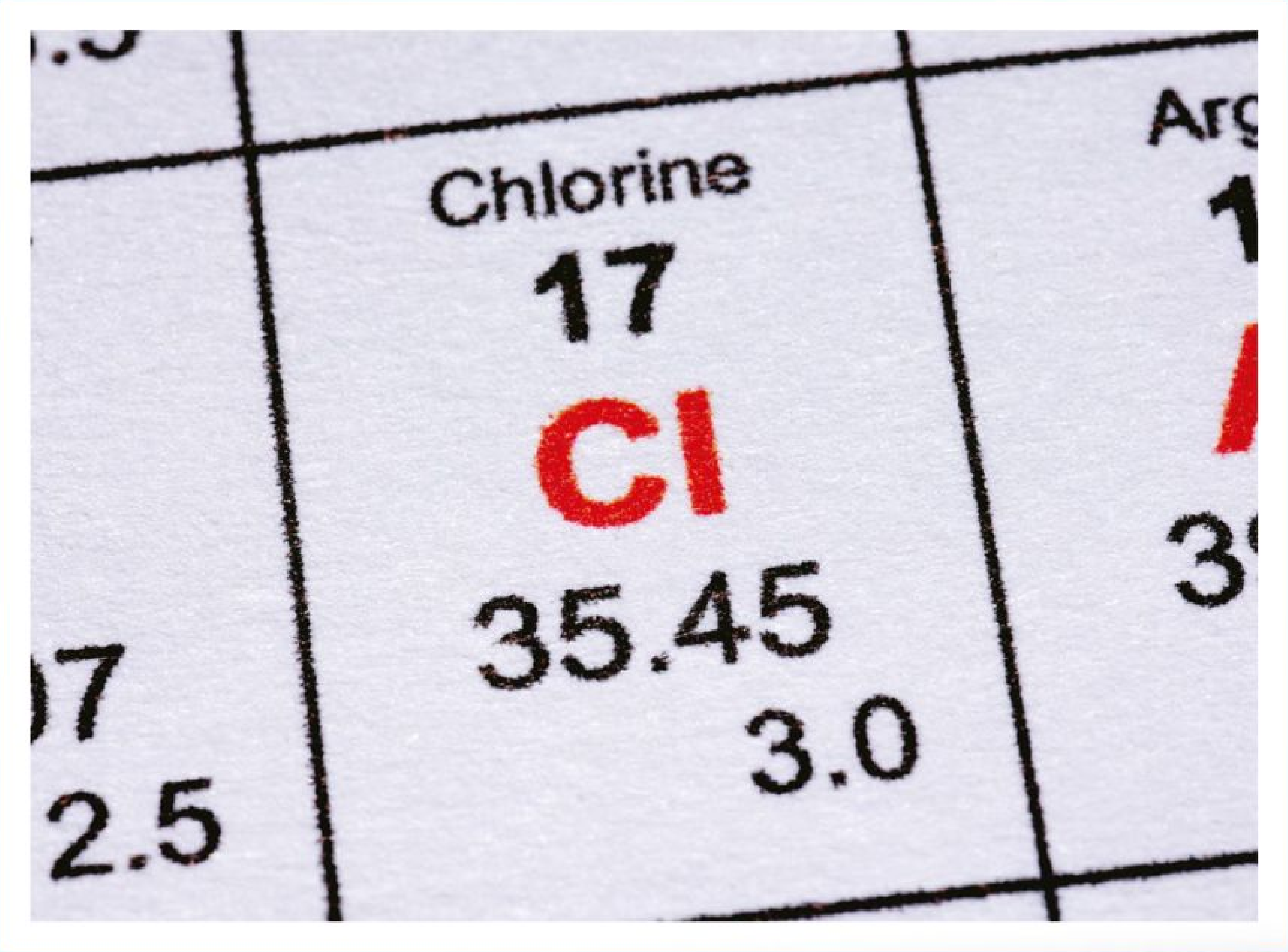
Caustic oven cleaner
Heavy-duty oven cleaners can be really caustic and corrosive, helping to break down fat and grease.

Caustic soda
Chemically known as sodium hydroxide, in its purest form it is a white solid and can cause severe burns due to its high alkalinity.

Base

A compound which 'accepts' hydrogen ions in an aqueous solution. Contains ions of the opposite charge. For example, hydroxide (OH-) which is naturally found in water and is negatively charged.

The eye irritation associated with chlorine is actually caused by the chemical reacting with human sweat



How does chlorine clean swimming pools?

The chemical reaction that stops swimmers from getting sick

With hundreds of people taking a dip each day, public swimming pools are a prime place for water-borne diseases, such as E. coli, to spread. Thankfully, a clever chemical can be used to keep your splashing sanitary.

When chlorine is added to pool water, it dissolves to form hypochlorous acid, a weak acid that acts as a disinfectant. It kills bacteria through a process called oxidation, which destroys protein structures inside the bacterial cells, causing them to die. As the water becomes more acidic, the hypochlorous acid itself splits up to form hypochlorite ions, which are less efficient at cleaning water. Therefore, for more effective disinfection, as well as comfortable swimming, the acidity of the pool water must be continuously monitored and kept at a neutral pH between 7.2 and 7.8.

Although it is effective at cleaning pools, chlorinated water also has some irritating side effects for swimmers. However, it's not the chlorine itself that's directly responsible for the red eyes we sometimes experience after a visit to the pool. This is the result of ammonia compounds, found in human sweat and urine, reacting with the hypochlorous acid to form chloromines, a compound that's also responsible for that strong chemical smell in swimming pools.

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How do fireworks make shapes?

The chemistry behind the spectacular patterns in the sky

Modern fireworks can burst into hearts, smiley faces and even a representation of the planet Saturn. The shape comes down to the construction of the firework's shell (container) and the arrangement of the exploding stars (pyrotechnic pellets) within them. As aerial shells are often spherical, they tend to explode symmetrically. Arranging the stars into the desired shape on a piece of card within the shell makes them explode outwards in that pattern.

Manufacturers also use multi-break shells that have different compartments inside them, often with stars of various colours and compositions. When these are placed and fused in a specific order, they will explode in sequence to create recognisable patterns and shapes in the sky. However, it's not an exact science; many displays will fire several copies of the same firework at the same time so that at least one of them creates the desired shape in the audience's line of sight.

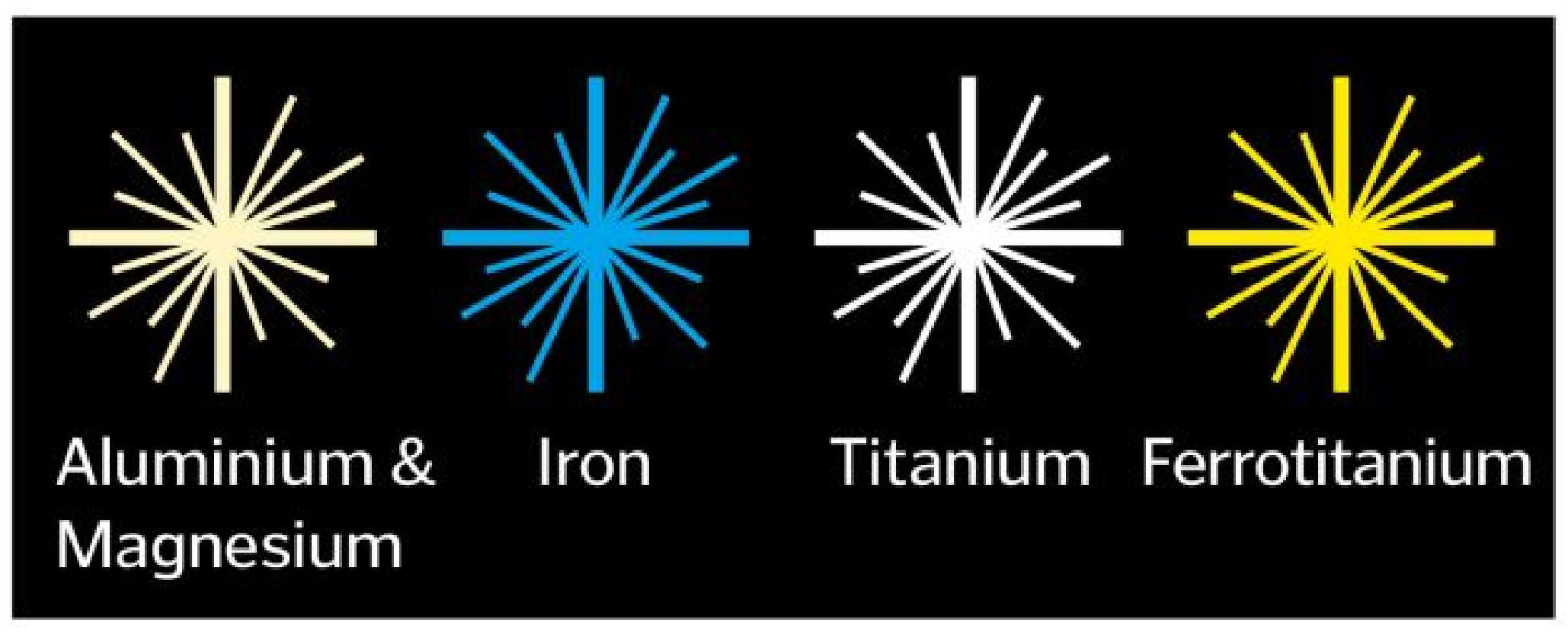
The first shaped fireworks appeared in the early 1990s to welcome returning American troops

Sparkler science

The chemical composition of sparklers consists of three important components: an oxidiser, a binder and a metal fuel. These three substances are bound together in a paste, which is then coated onto the iron wire that forms the sparkler's main body.

A powdered metal is essential, as it helps produce sparks that generate the famous glittery effect and can also colour the sparkler. Aluminium, titanium and magnesium all produce bright, white sparks, whereas iron will burn with a characteristic orange hue. When iron and titanium are combined they form an alloy called ferrotitanium, which produces golden yellow sparks when it burns.

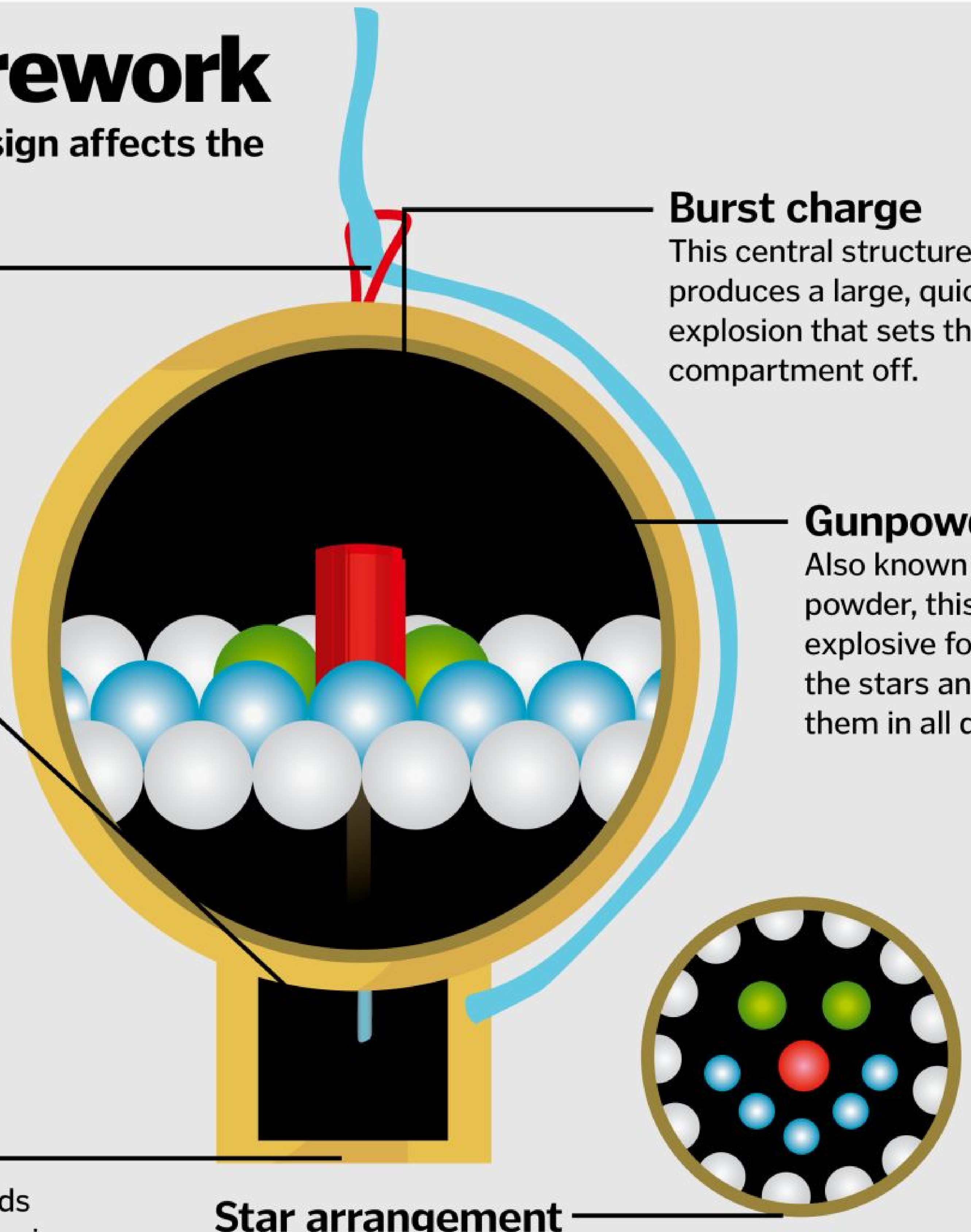
For even more colours, salts of various metals can be added to sparklers, which is often the technique used for creating coloured fireworks. Copper salts produce green-blue, barium salts create green and strontium salts produce red.



Powdered metals react with oxygen to produce metal oxides, which burn with specific colours

Inside a firework

See how the internal design affects the shape of the explosion



Fuse
This initial fuse ignites other, smaller fuses within the firework. In public displays, these are lit by electrical contacts called wirebridge fuseheads.

Burst charge
This central structure produces a large, quick explosion that sets the entire compartment off.

Gunpowder
Also known as black powder, this provides the explosive force that ignites the stars and launches them in all directions.

Timed fuse
This section ignites the burst charge once the firework has reached the appropriate altitude.

Lifting charge
The initial explosion sends the shell soaring into the air without detonating the main compartment.

Star arrangement
Different chemicals are added to create a range of colours, while the shape is determined by the arrangement of small, combustible pellets.

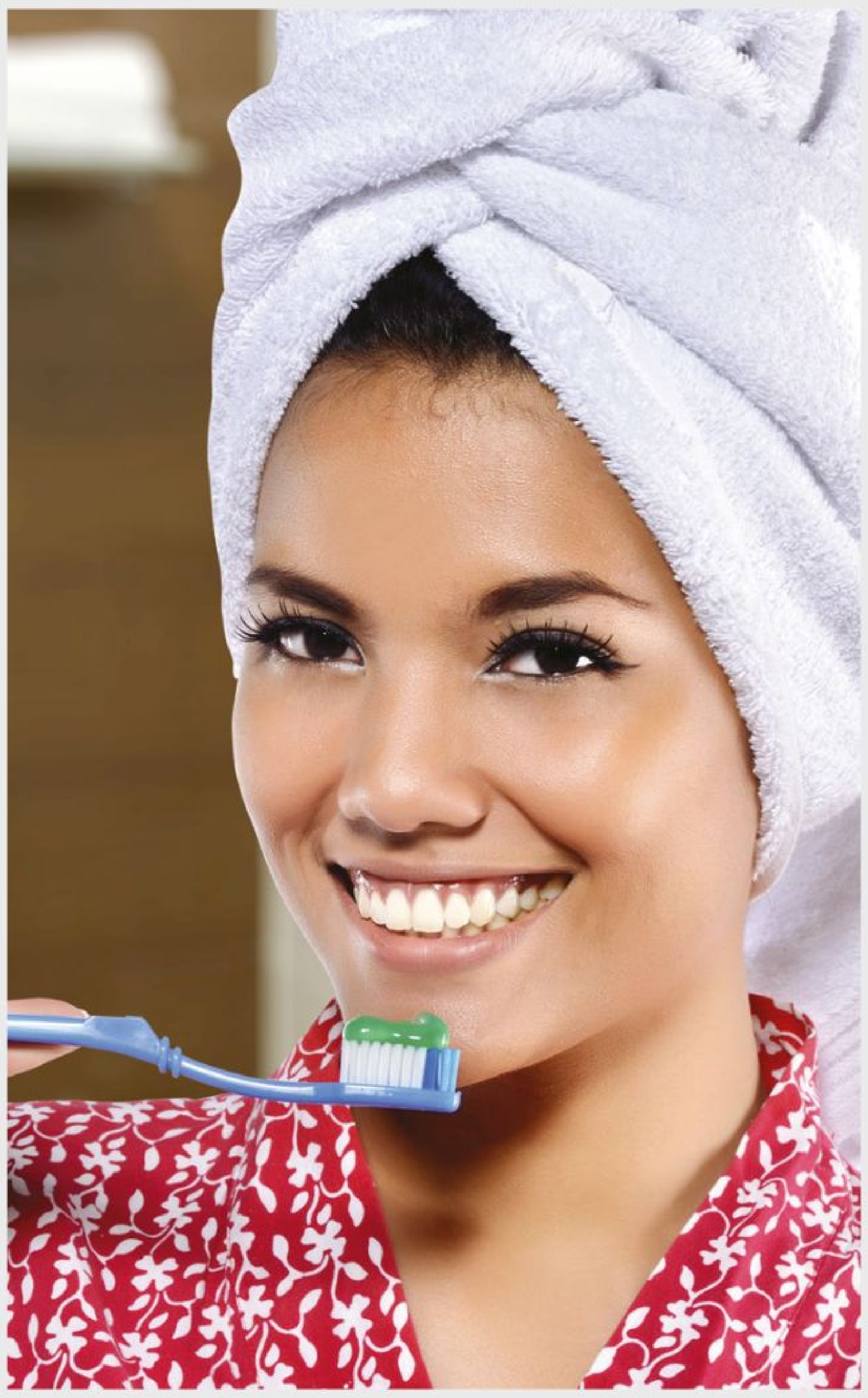
© Thinkstock

Fluoride explained

How this mineral can protect your pearly whites

Fluoride is a mineral found naturally in water, soil, and in trace amounts in tea and fish. Fluoride can be used as a biochemical agent, but its main use is to help prevent the formation of tooth decay. Around 70 years ago, researchers found that people who drank water containing more fluoride had less tooth decay. This discovery led to the introduction of schemes around the world to add fluoride to water supplies where the level was low.

The substance also became commonplace in many brands of toothpaste. Fluoride protects teeth by encouraging a stronger enamel to form that's more resistant to acid attack. It also reduces plaque bacteria's ability to produce acid – the primary cause of tooth decay. However, it seems that you can have too much of a good thing. Recently in the US, the fluoride in water has been found to cause white splotches on children's teeth – a condition known as dental fluorosis – so the government has lowered fluoride levels. As long as the standard guidelines are followed, fluoride really can be beneficial to your dental health.



Fluoride is used in toothpaste to help fight decay

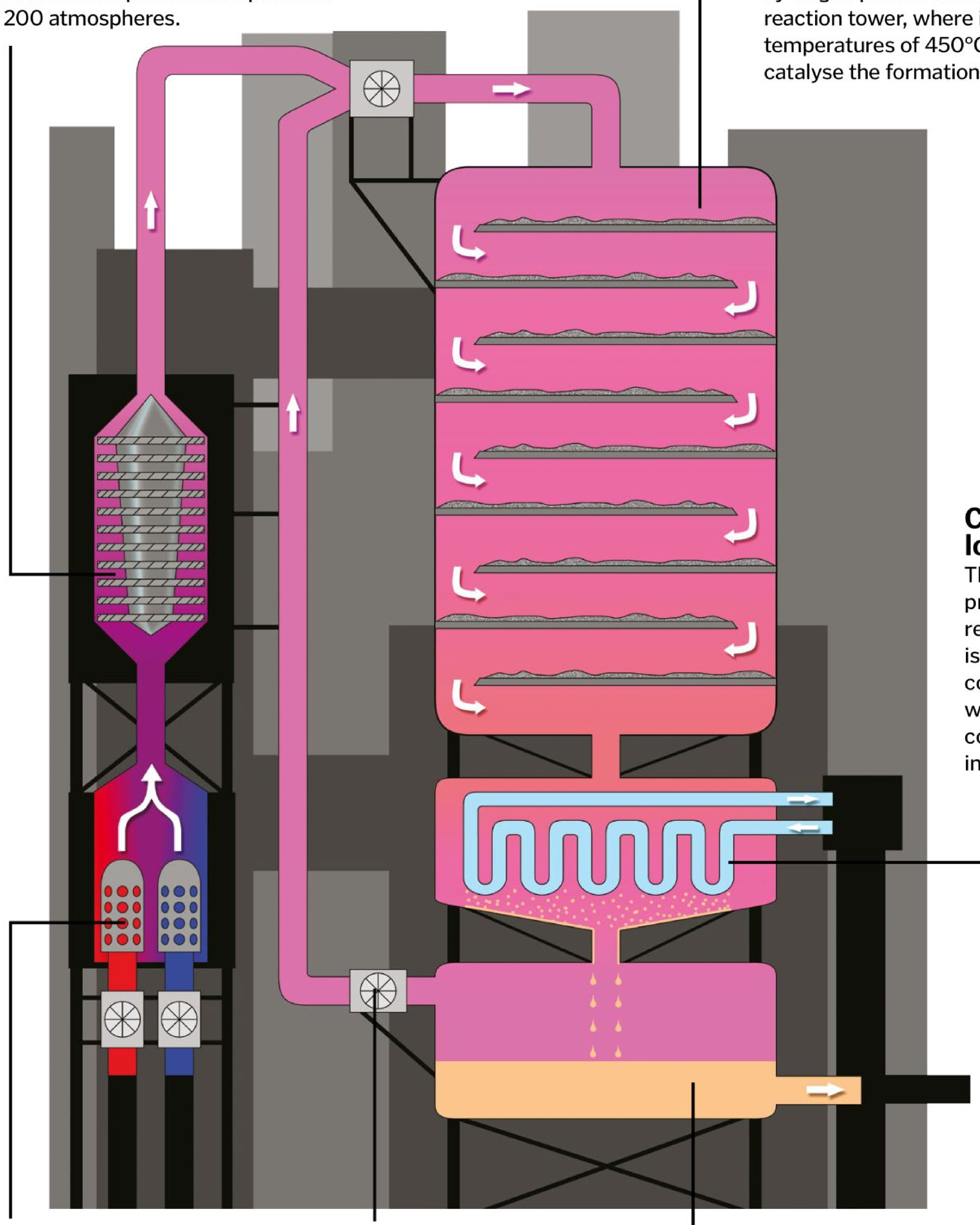
Making fertiliser

How the Haber process helps us grow food

The Haber process is an efficient way of producing ammonia for use in fertilisers and household products. Ammonia has helped to sustain food production for billions of people, but its use in explosives has reportedly resulted in the death of 150 million. It's for this reason that some scientists say ammonia changed the course of the 20th century more than electricity or television.

Industrial production of ammonia

The ins and outs of the Haber process



Gas compression
The clean hydrogen and nitrogen are mixed and compressed at a pressure of 200 atmospheres.

Reaction tower
The mixture of nitrogen and hydrogen passes through the reaction tower, where iron and high temperatures of 450°C (842°F) catalyse the formation of ammonia.

Cooling loop
The ammonia produced in the reaction tower is gaseous. The cooling loop works to condense it into a liquid.

Nitrogen and hydrogen cleaning
Before the process can begin, the nitrogen and hydrogen need to be cleaned and purified.

Gas recycling
The process doesn't react all the hydrogen and nitrogen together; therefore any left over gas can be recycled back into the reaction tower.

Ammonia collection
Once condensed, the liquid ammonia is piped off for collection, and can be stored in a refrigerator.

© Science Photo Library; Thinkstock

Crystallised alcohol

The hidden beauty of our favourite alcoholic drinks

If you leave a drop of an alcoholic beverage, to dry out, the water and alcohol will eventually evaporate to leave behind crystallised sugar. If you then look at this sugar through a polarising microscope, you will see a pattern of bright colours as light refracts through the crystals. The effect is created using two polarising filters, one between the crystals and the light underneath them, and another positioned at a 90-degree angle from it, between the crystals and the microscope lens above them. As these filters force light waves to oscillate in one direction, rather than all different directions as they would normally, the two polarising filters should block the light completely. But when the light passes through the crystals, it refracts, allowing it to pass through the filters at different angles so we see lots of vibrant colours. Geologists use the same technique to study the structure and composition of rocks.

> *"When light passes through the crystals, it refracts, allowing it to pass through the filters at different angles"*

© Rex Features

YOUR GUIDE TO

How these chemical building blocks make up life, the universe and everything

All of the 118 elements in the periodic table are made from the same three key ingredients – protons, neutrons and electrons. The protons and neutrons make up the nucleus at the centre of each atom, while the electrons whizz around the outside and make chemical bonds with other atoms. The identity of each atom is determined by the number of protons in its nucleus, known as the atomic number. Hydrogen has one, helium has two, lithium three, and so on. The periodic table lists the elements in this order.

Protons are positively charged, while electrons are negatively charged; an atom will have an equal number of each. The electrons are arranged in 'shells' around the nucleus. Each row of the periodic table represents a new layer of electron shells, and each column represents how full the outer shell is. For example, elements in the first column of the periodic table – including lithium and sodium – have just one electron in their outer shell, while those in the second column – such as beryllium and magnesium – have two.

The number of electrons in the outer shell affects how the element behaves, so those in the same column have similar properties. Atoms like to have a full outer shell of electrons, so those with one or two extras are keen to give them away, and those with gaps want to fill them up. If you drop any of the elements from the first column into water, they will fizz, flame or even explode as they race to share their spare electron with other atoms, but if you did the same with the elements in the last column, nothing would happen. These elements have a full outer shell, so don't need to share their electrons with other atoms.

Most of the elements in the periodic table occur naturally on Earth, but any element heavier than lead (number 82) is unstable and gradually undergoes radioactive decay. Elements heavier than uranium (number 92) have to be made artificially. Join us as we explore the periodic table, and delve into the elements that shape our everyday lives. ✲

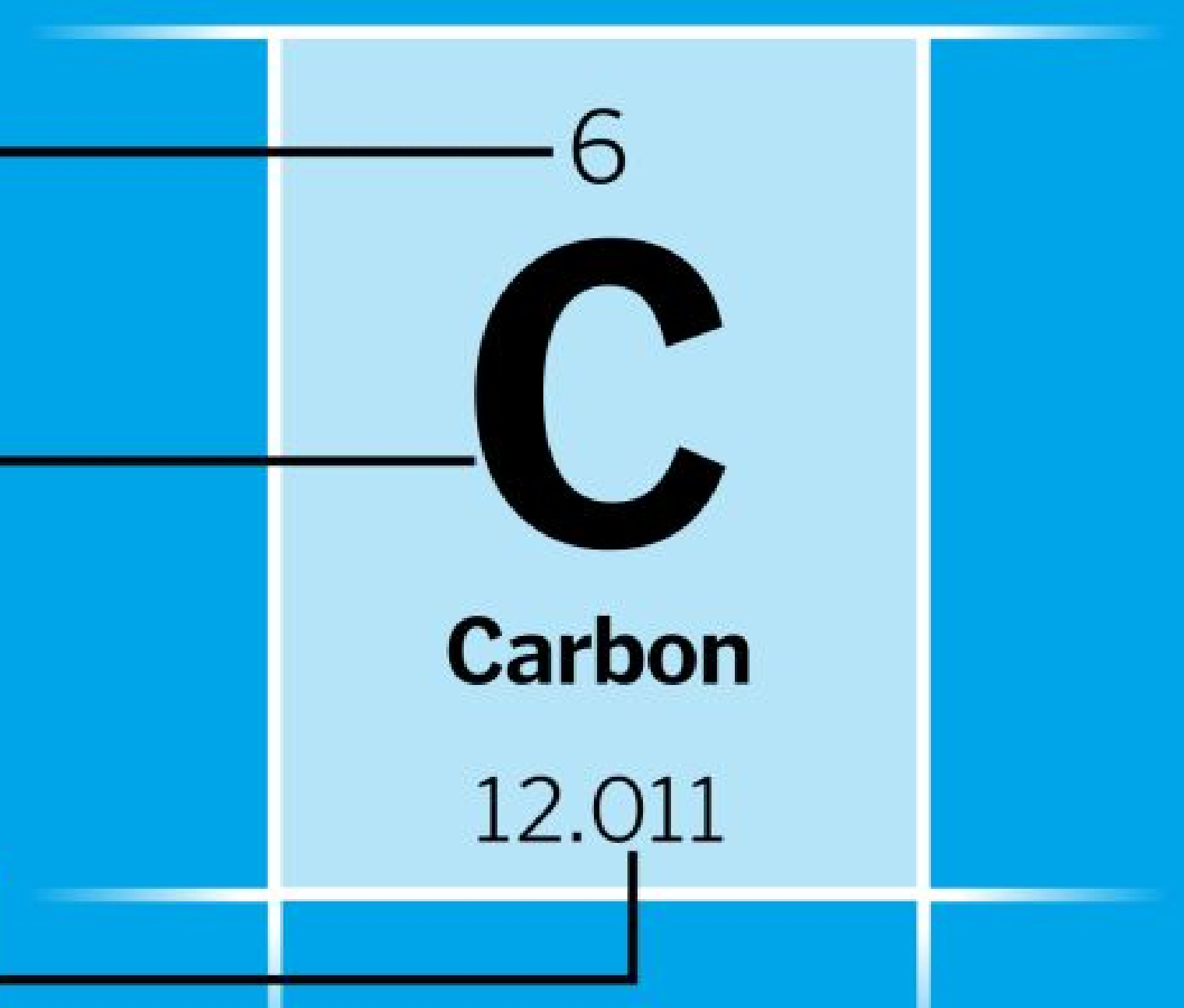
How to read the periodic table

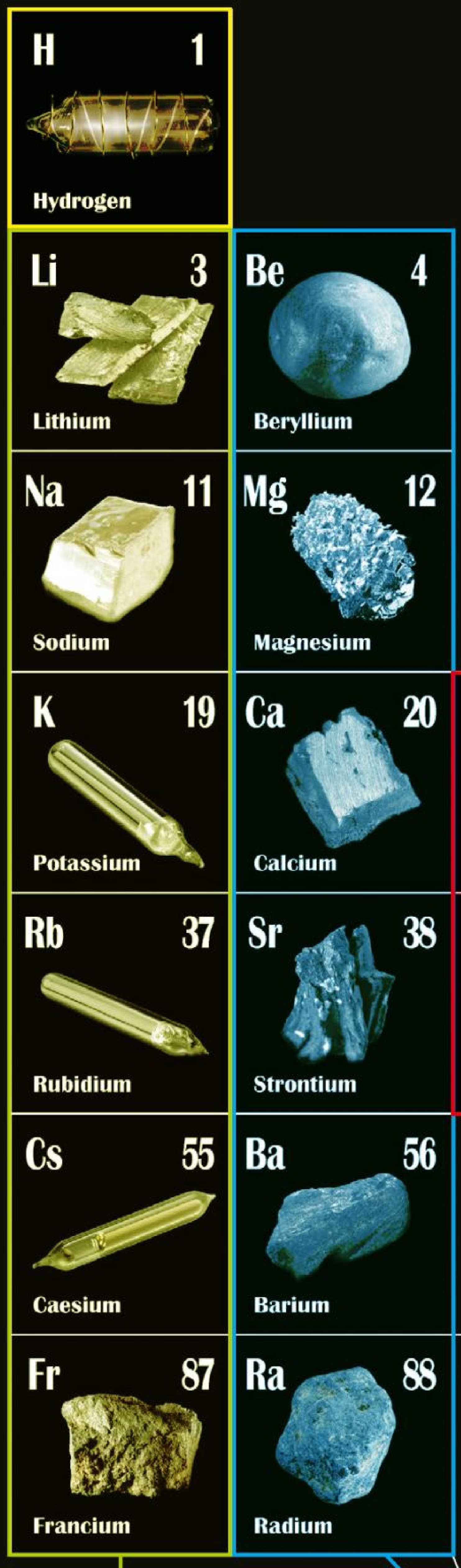
There are three key pieces of information about each element to look out for

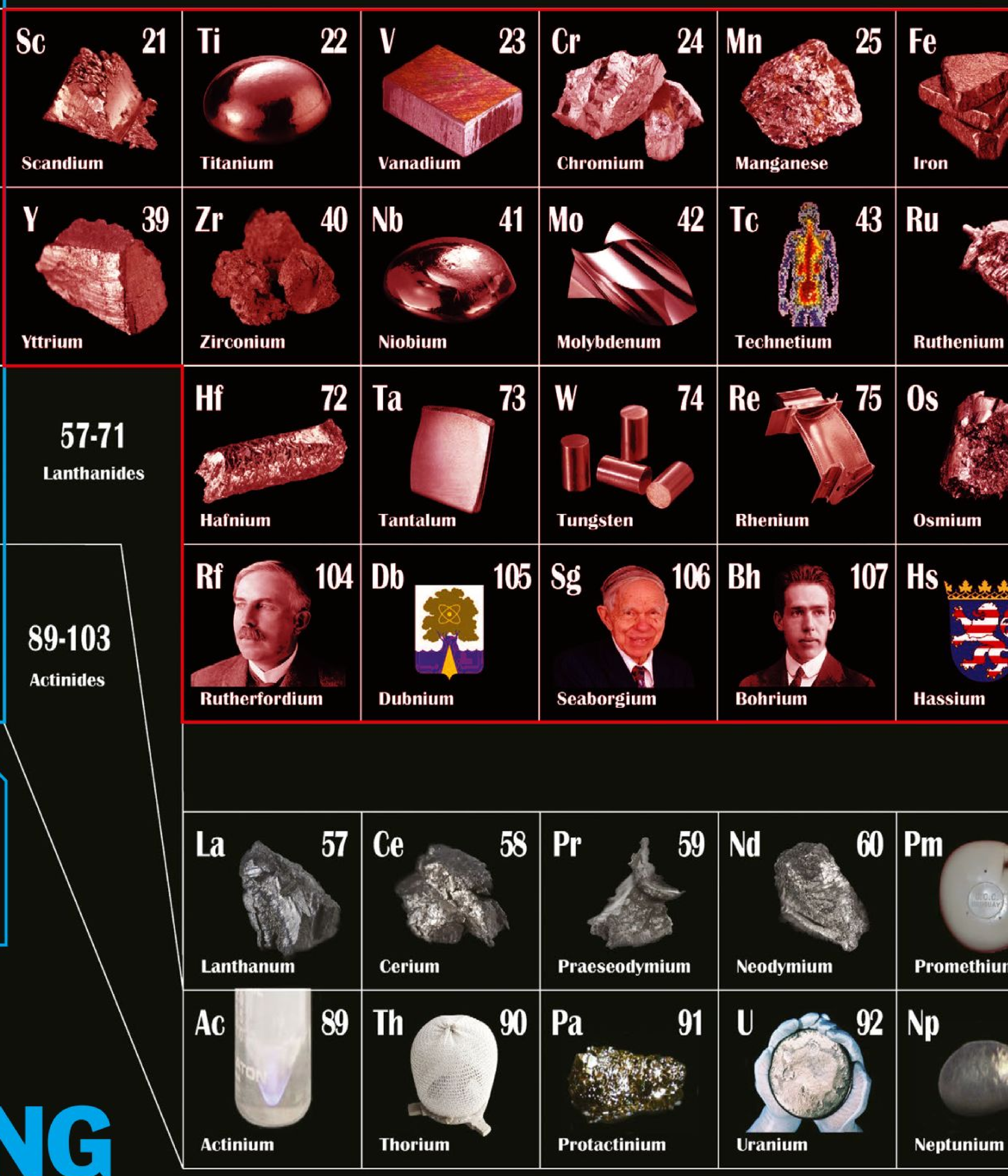
Atomic number
The atomic number tells you how many protons each atom has. This is different for every element.

Chemical symbol
Each element has a one or two letter symbol. It is often based on Latin, and may not relate to the English name.

Atomic mass
Some tables also give the atomic mass, which corresponds to the total number of protons and neutrons in the atom.







Alkali metals
These elements each have a spare electron. They are highly reactive and, in nature, are always found bound to other elements.

Alkaline earth metals
These elements have two spare electrons, and are also highly reactive. Like the alkali metals, they do not naturally exist on their own.

SPOTTING PATTERNS

The chemical elements have more in common than you might think

THE ELEMENTS

Filling in the gaps

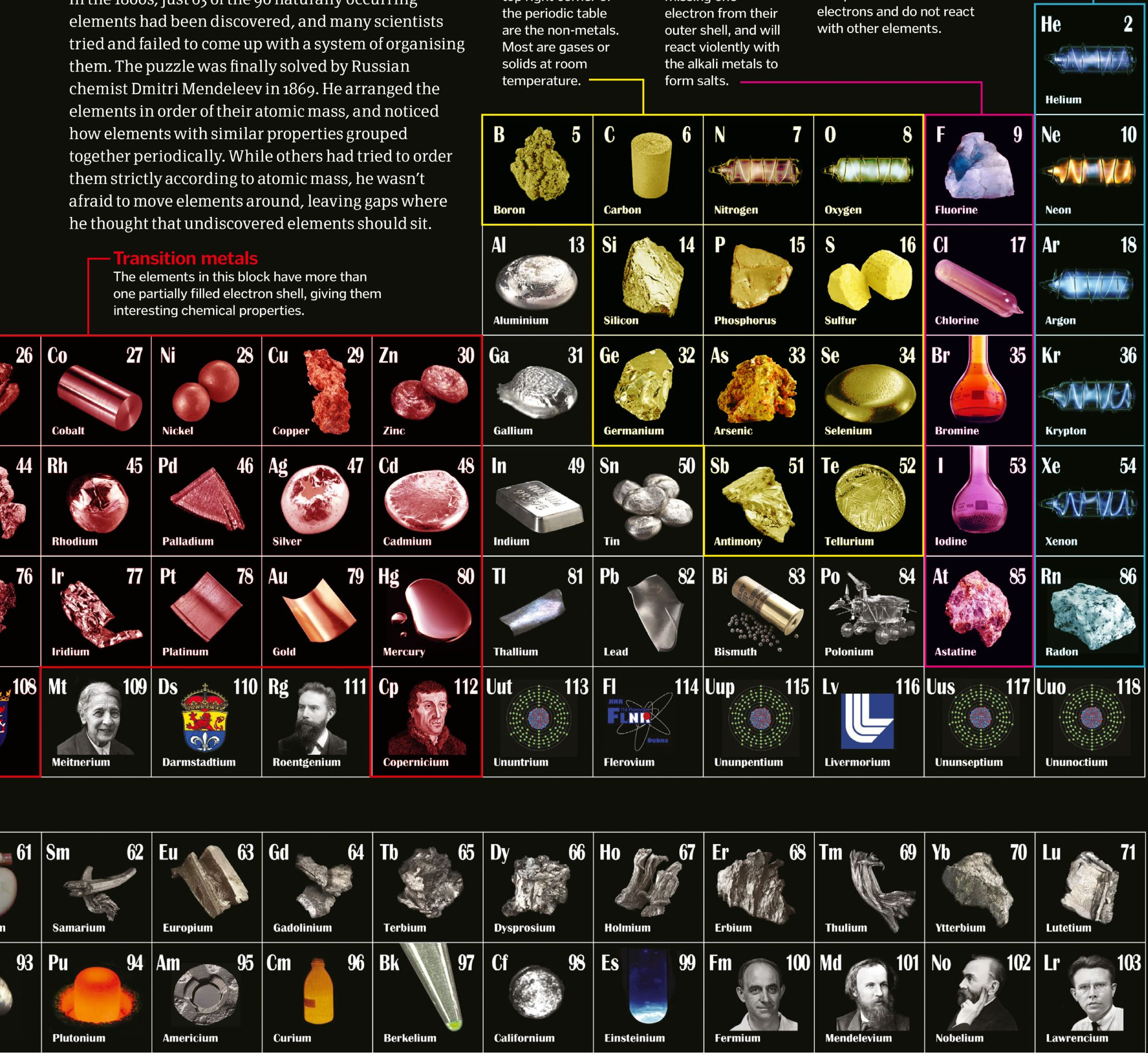
In the 1800s, just 63 of the 90 naturally occurring elements had been discovered, and many scientists tried and failed to come up with a system of organising them. The puzzle was finally solved by Russian chemist Dmitri Mendeleev in 1869. He arranged the elements in order of their atomic mass, and noticed how elements with similar properties grouped together periodically. While others had tried to order them strictly according to atomic mass, he wasn't afraid to move elements around, leaving gaps where he thought that undiscovered elements should sit.

Non-metals
The elements in the top right corner of the periodic table are the non-metals. Most are gases or solids at room temperature.

Halogens
The halogens are missing one electron from their outer shell, and will react violently with the alkali metals to form salts.

Noble gases
These elements have a complete outer shell of electrons and do not react with other elements.

Transition metals
The elements in this block have more than one partially filled electron shell, giving them interesting chemical properties.



										He 2 Helium
					B 5 Boron	C 6 Carbon	N 7 Nitrogen	O 8 Oxygen	F 9 Fluorine	Ne 10 Neon
					Al 13 Aluminium	Si 14 Silicon	P 15 Phosphorus	S 16 Sulfur	Cl 17 Chlorine	Ar 18 Argon
26	Co 27 Cobalt	Ni 28 Nickel	Cu 29 Copper	Zn 30 Zinc	Ga 31 Gallium	Ge 32 Germanium	As 33 Arsenic	Se 34 Selenium	Br 35 Bromine	Kr 36 Krypton
44	Rh 45 Rhodium	Pd 46 Palladium	Ag 47 Silver	Cd 48 Cadmium	In 49 Indium	Sn 50 Tin	Sb 51 Antimony	Te 52 Tellurium	I 53 Iodine	Xe 54 Xenon
76	Ir 77 Iridium	Pt 78 Platinum	Au 79 Gold	Hg 80 Mercury	Tl 81 Thallium	Pb 82 Lead	Bi 83 Bismuth	Po 84 Polonium	At 85 Astatine	Rn 86 Radon
108	Mt 109 Meitnerium	Ds 110 Darmstadtium	Rg 111 Roentgenium	Cp 112 Copernicium	Uut 113 Ununtrium	Fl 114 Flerovium	Uup 115 Ununpentium	Lv 116 Livermorium	Uus 117 Ununseptium	Uuo 118 Ununoctium
61	Sm 62 Samarium	Eu 63 Europium	Gd 64 Gadolinium	Tb 65 Terbium	Dy 66 Dysprosium	Ho 67 Holmium	Er 68 Erbium	Tm 69 Thulium	Yb 70 Ytterbium	Lu 71 Lutetium
93	Pu 94 Plutonium	Am 95 Americium	Cm 96 Curium	Bk 97 Berkelium	Cf 98 Californium	Es 99 Einsteinium	Fm 100 Fermium	Md 101 Mendelevium	No 102 Nobelium	Lr 103 Lawrencium

© SPL

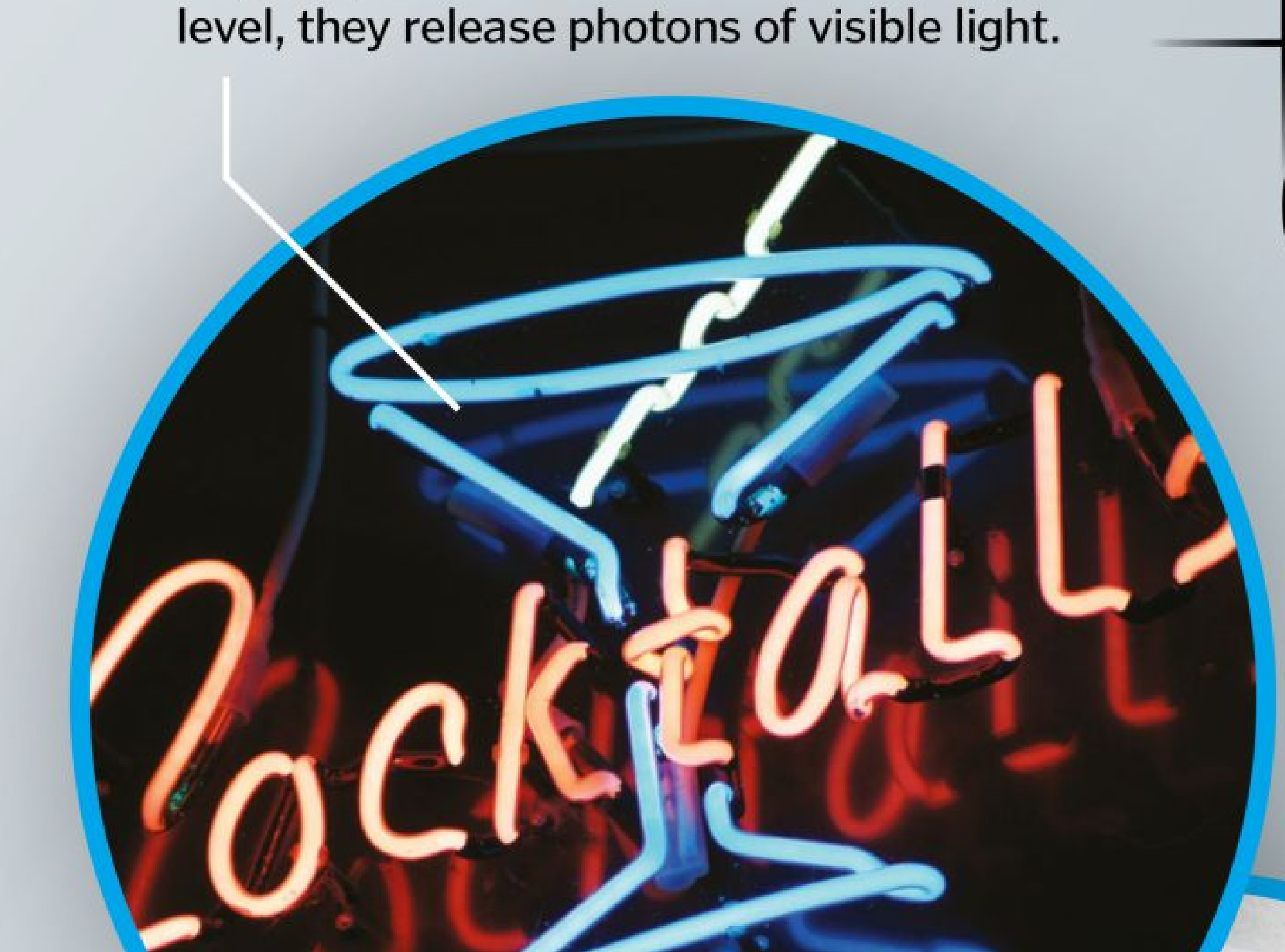
> *"The puzzle was finally solved by Dmitri Mendeleev in 1869"*

Everyday elements

Look around and you'll discover dozens of different elements

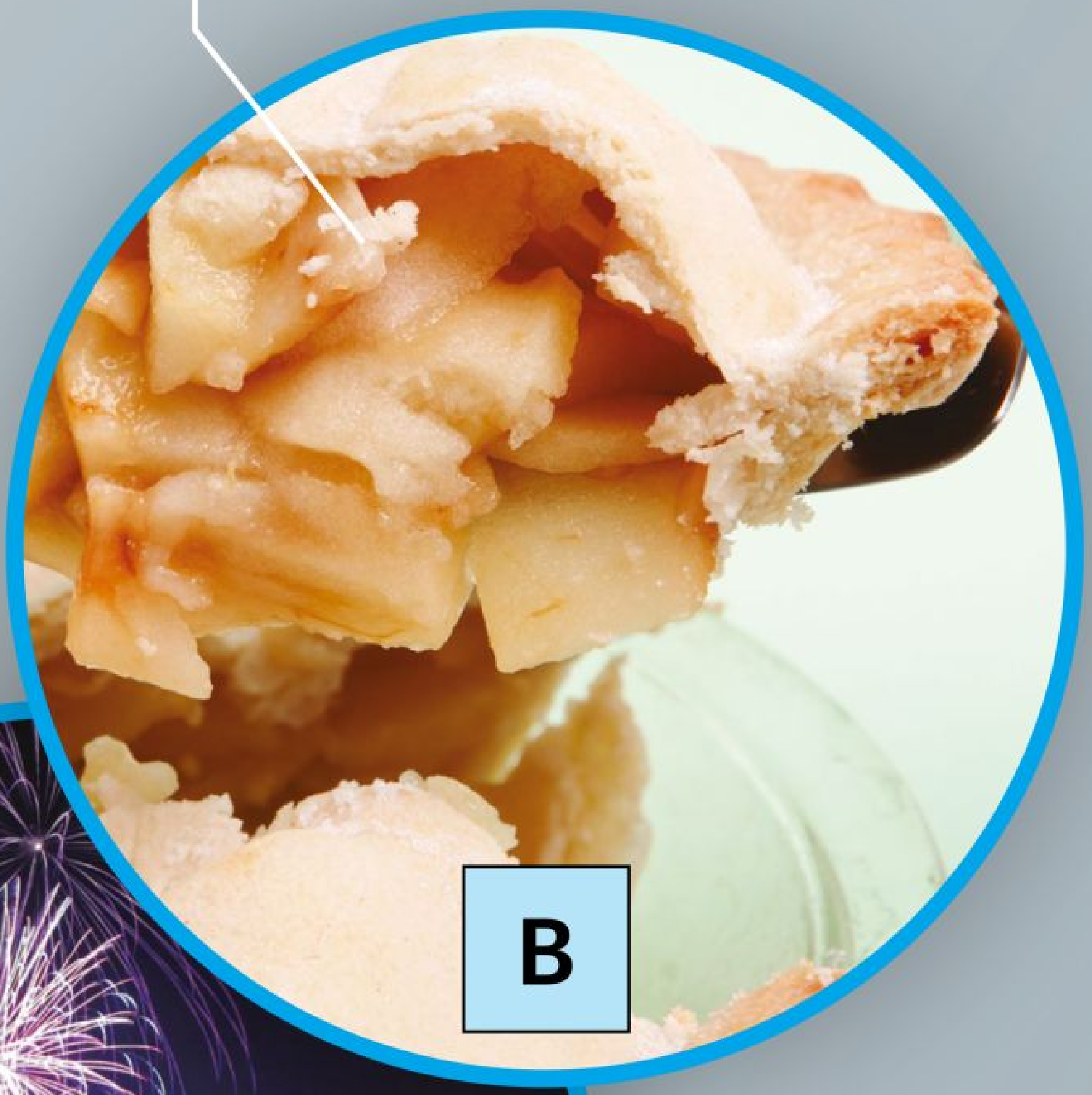
Gas-discharge lamps

These lamps typically contain neon, argon, krypton, or xenon, which are noble gases. When an electric current is passed through the gases, they become excited, and when they drop back down to a normal energy level, they release photons of visible light.



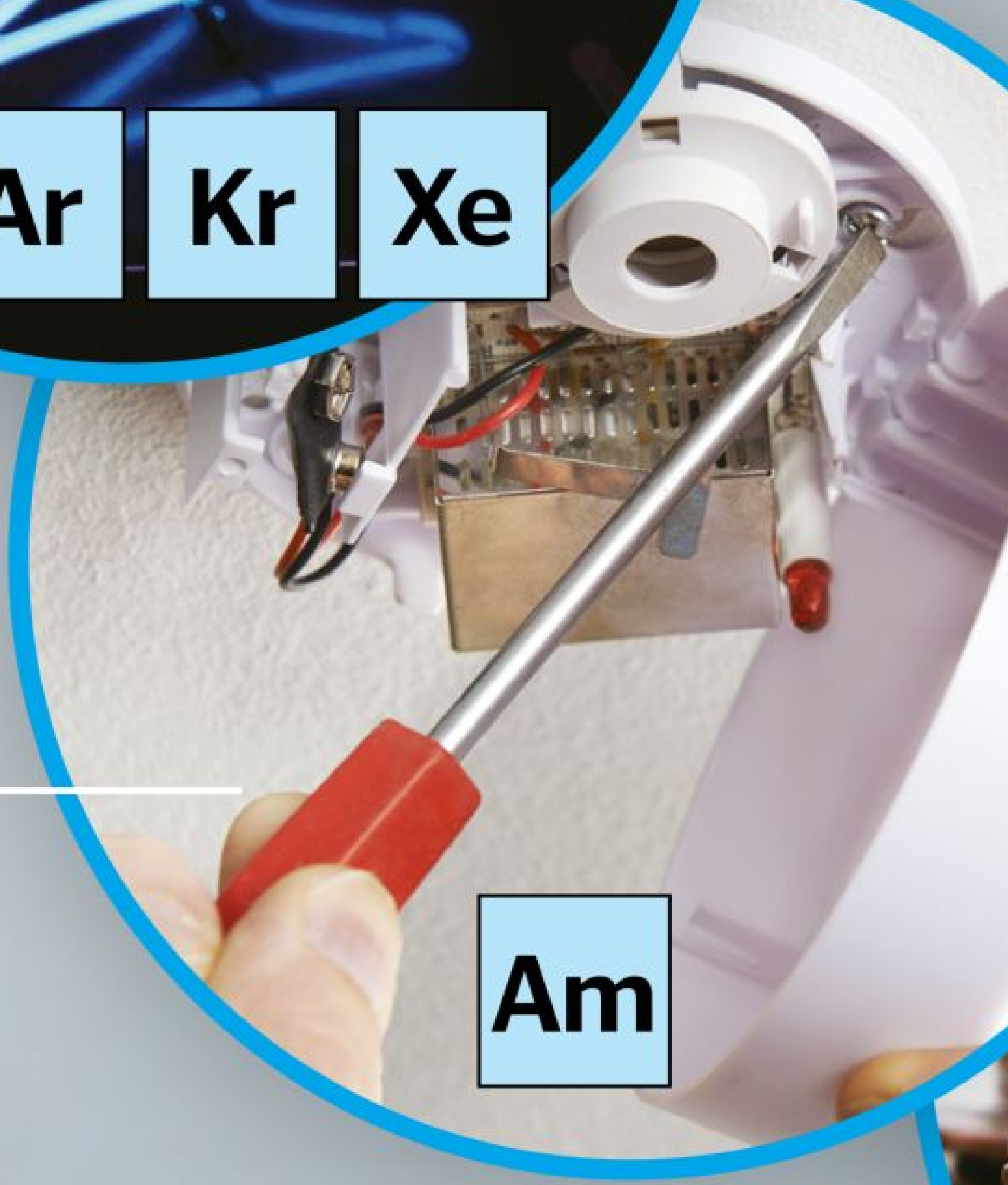
Heat resistant glass

Borosilicate glass, which is found in the kitchen and in the lab, contains at least five per cent boron oxide. Boron has a high melting point, which helps the glass to resist thermal shock, going from hot to cold and back again without shattering.



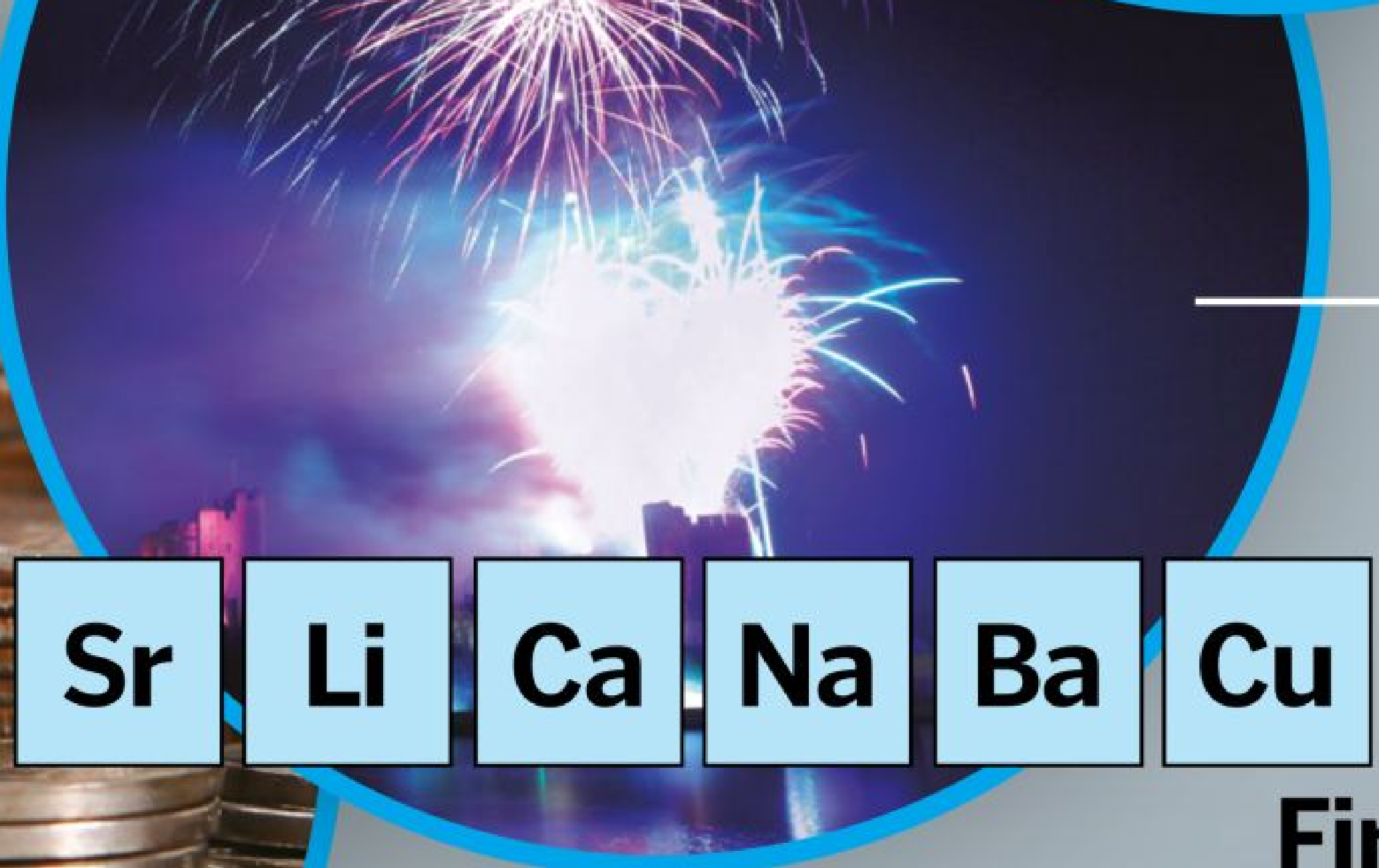
Coins

In the UK, 1p and 2p coins are made from copper-plated steel (iron and carbon), 5p and 10p coins are nickel-plated steel, 20p and 50p coins are cupro-nickel (copper and nickel), and £1 and £2 coins are nickel-brass (copper, nickel and zinc). These elements are cheaper than gold or silver, and durable too.



Smoke detectors

Many smoke detectors contain small amounts of americium. This radioactive element releases alpha particles, which 'knock' electrons away from gases in the air and towards a positively charged plate in the smoke detector, generating a current. When smoke gets in the way, the current stops and the alarm sounds.



Fireworks

The colours of fireworks are produced using various combinations of elements, which burn with different coloured flames. Strontium and lithium salts burn red and calcium salts burn orange, while sodium salts burn yellow, barium salts green, and copper salts blue. Purple can be made by mixing strontium and copper.

Phone ingredients

The shiny metal, glass and plastic exteriors of smartphones can contain lots of different elements, including aluminium, magnesium, carbon, and oxygen, but this is just the tip of the iceberg; the circuitry, battery, cameras and speakers contain dozens more. Silicon chips coated with antimony and arsenic sit beside batteries containing lithium and cobalt, and the features that we take for granted, like colour screens, are made possible by rare Earth metals like terbium and europium. Finding uses for all of these elements is a real achievement, but as demand for electronics soars, our limited resources could start to run out.

In Sn O

Indium tin oxide film

Three elements – indium, tin and oxygen – make up the conductive film inside touch screens.

Al Si O K

Aluminosilicate glass

This tough glass is made from a mixture of aluminium, silicon, oxygen and potassium.

Li Co O

Lithium ion battery

The positive electrode contains lithium, cobalt and oxygen, and the negative electrode is made from carbon.

La Gd Dy

Rare earth circuitry

Smartphone circuitry contains rare earth metals like lanthanum, gadolinium and dysprosium.

Cu Ag Au Ta

Precious metal wiring

Copper, silver, gold and tantalum are used in micro-electrical components and wiring.

YOU ARE MADE OF STARDUST

The elements that make up our bodies were forged inside ancient stars

Hydrogen is the smallest element, and formed in vast quantities after the Big Bang, along with a less plentiful supply of helium, and even smaller amounts of lithium and beryllium. But making the heavier elements required more energy. Hydrogen and helium gas clumped together to form clouds, and these clouds collapsed to form stars with enough heat and pressure to trigger nuclear fusion; inside the stars, the nuclei of hydrogen atoms slammed together, fusing to form helium.

As the stars aged, the helium atoms started to create even heavier elements, including carbon, nitrogen and oxygen. Depending on the mass of the star, this process sometimes continued, producing the nuclei of most of the elements up to number 26, iron. After this critical point, fusion reactions stop releasing energy. When stars run out of useable fuel, they collapse, kicking layers of gas and heavy elements out into space.

For the most massive stars, this process involves a powerful explosion called a supernova, which provides enough energy to make the elements that are heavier than iron. The remnants of these old exploded stars mix with yet more hydrogen gas and go on to make more star systems, like our own Sun and planets, providing us with the range of elements we have on Earth today.

> *"The remnants of old exploded stars go on to make more star systems"*

65% O

OXYGEN

Oxygen makes up over half of our body weight. It is one of the key components of water, and is one of the three essential elements needed to make biological molecules like fat and protein.

18.5% C

CARBON

Carbon can make four bonds to other elements, making it the perfect scaffolding for building large, complex molecules. It is an essential component of fats, proteins, sugars and DNA.

9.5% H

HYDROGEN

Hydrogen is the third element found in all biological molecules. There are actually more hydrogen atoms in the body than carbon or oxygen, but they are much lighter.

3.2% N

NITROGEN

Oxygen, carbon and hydrogen make up the core of all biological molecules, but lots of other elements are used in smaller amounts. Nitrogen is found in both DNA and protein.

1.5% Ca

CALCIUM

Calcium is found in bones and teeth, and also plays an important role in signalling between cells, in muscle and nerve function, and in blood clotting.

P 1%

PHOSPHORUS

Phosphorus, like calcium, helps to provide strength to bones and teeth. It is also involved in energy use, and is a vital component in DNA, helping to hold the whole structure together.

0.4%

POTASSIUM

Potassium ions are found dissolved inside cells and in body fluids. They carry an electric charge, and are used by nerve cells and muscle cells in the transmission of electrical impulses.

K

S 0.3%

SULPHUR

Sulphur is found in some of the building blocks of protein. It can make strong bonds to other sulphur atoms, helping to fix proteins into their 3D shapes.

Na 0.2%

SODIUM

Sodium is another electrolyte that carries charge inside the body. Along with potassium and chlorine, it is one of the key elements responsible for normal nerve and muscle function.

0.4%

AND THE REST

There are many other elements in the human body, including chlorine, magnesium, manganese, iron, fluorine, cobalt, copper, zinc, selenium, molybdenum, iodine, lithium, and aluminium.

Cl Mg Mn Fe F Co
Cu Zn Se Mo I Li Al

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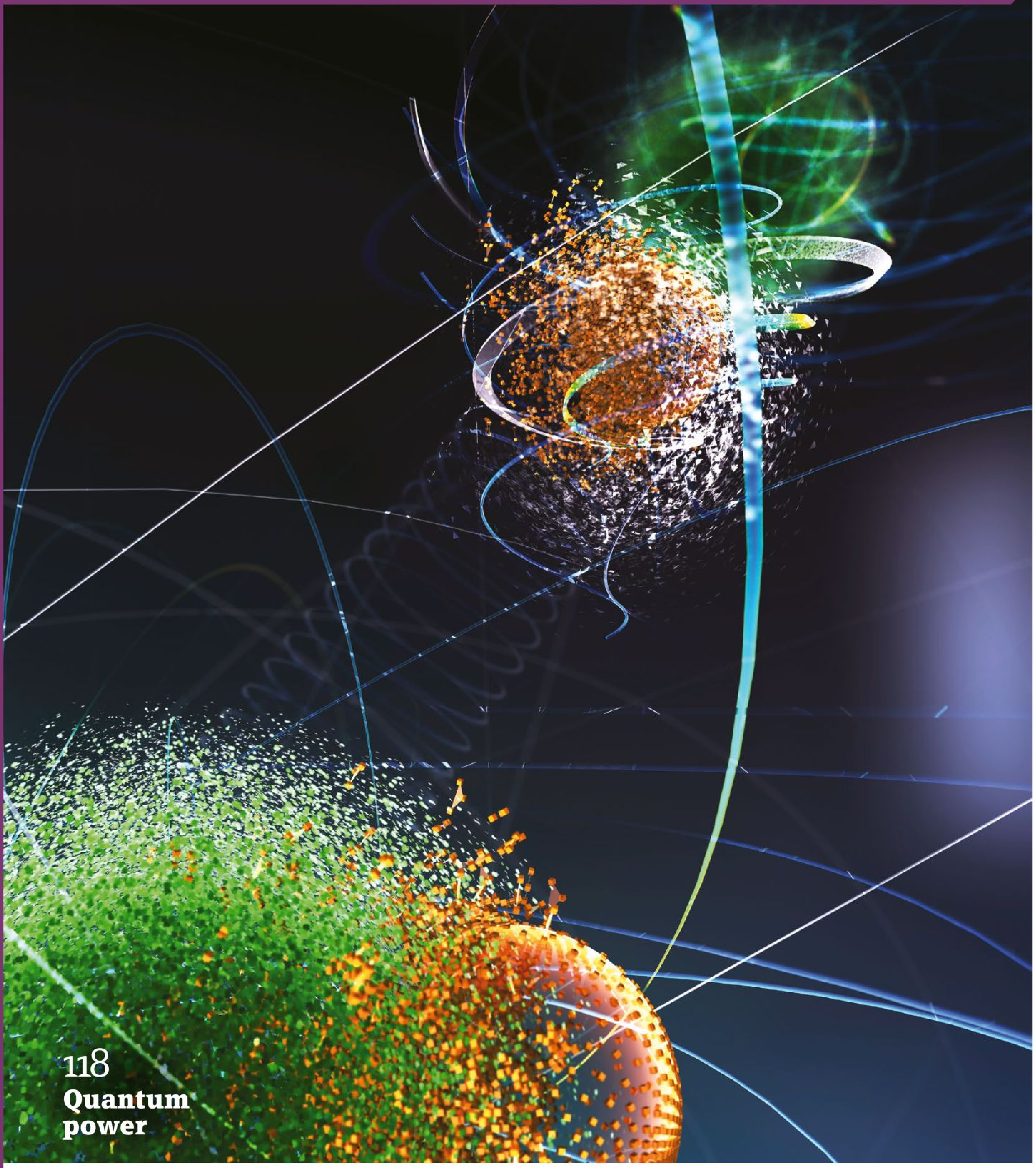
PHYSICS



118
Quantum power

126
The Large Hadron Collider

138
The science of music

118 **Quantum power**
126 **The Large Hadron Collider**
128 **60 second science**
138 **The science of music**
144 **Batteries**
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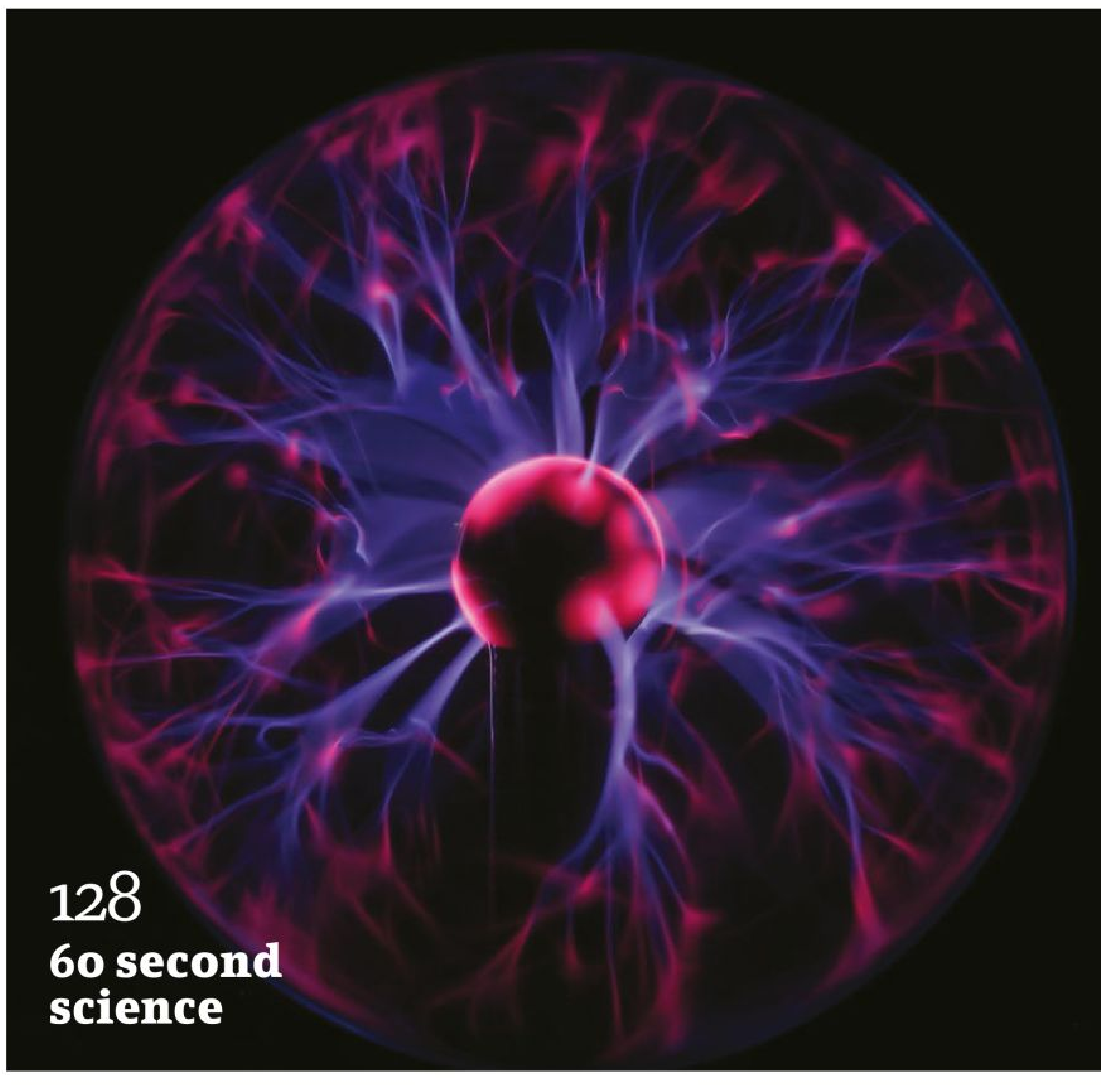
158
Balloon popping science



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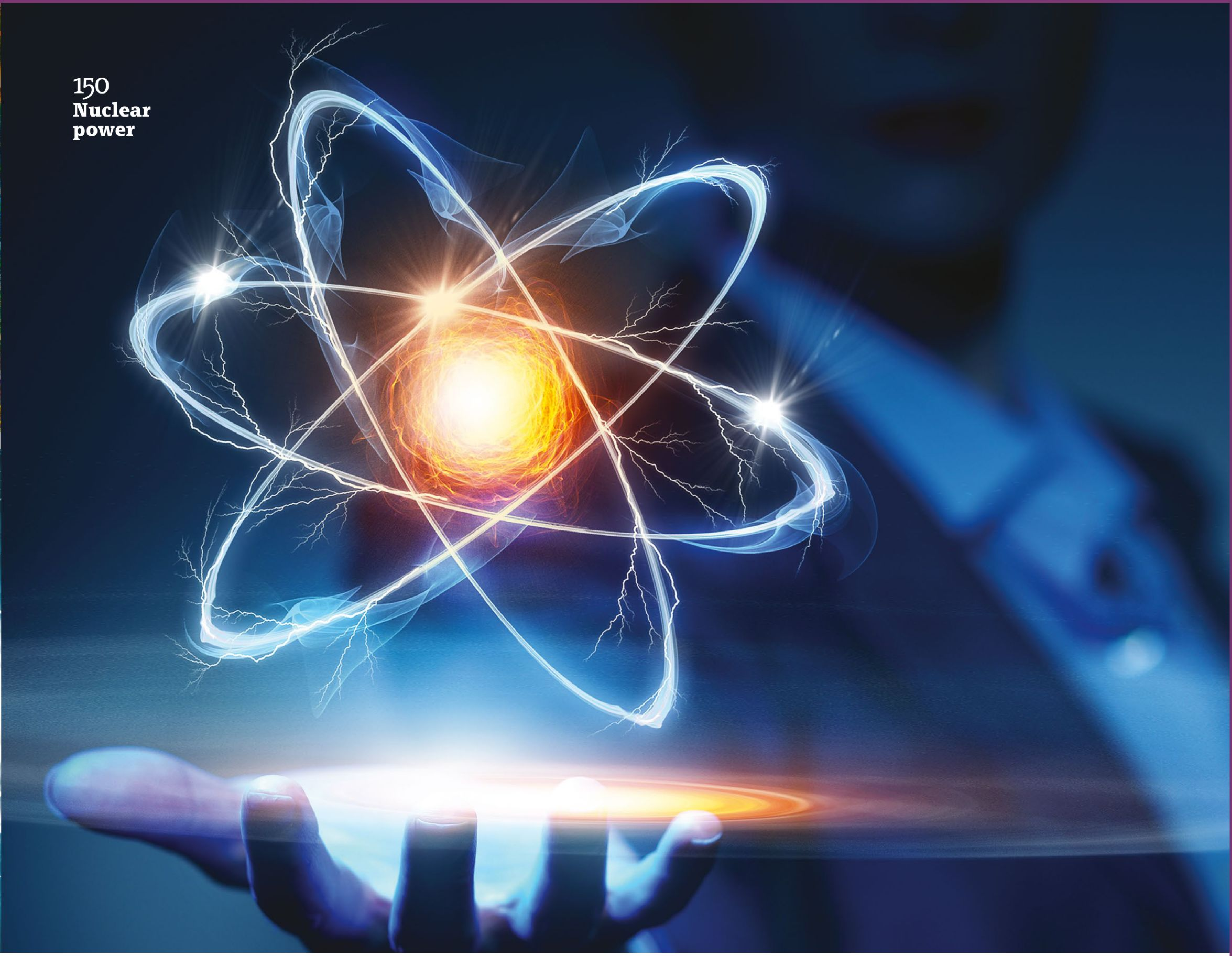
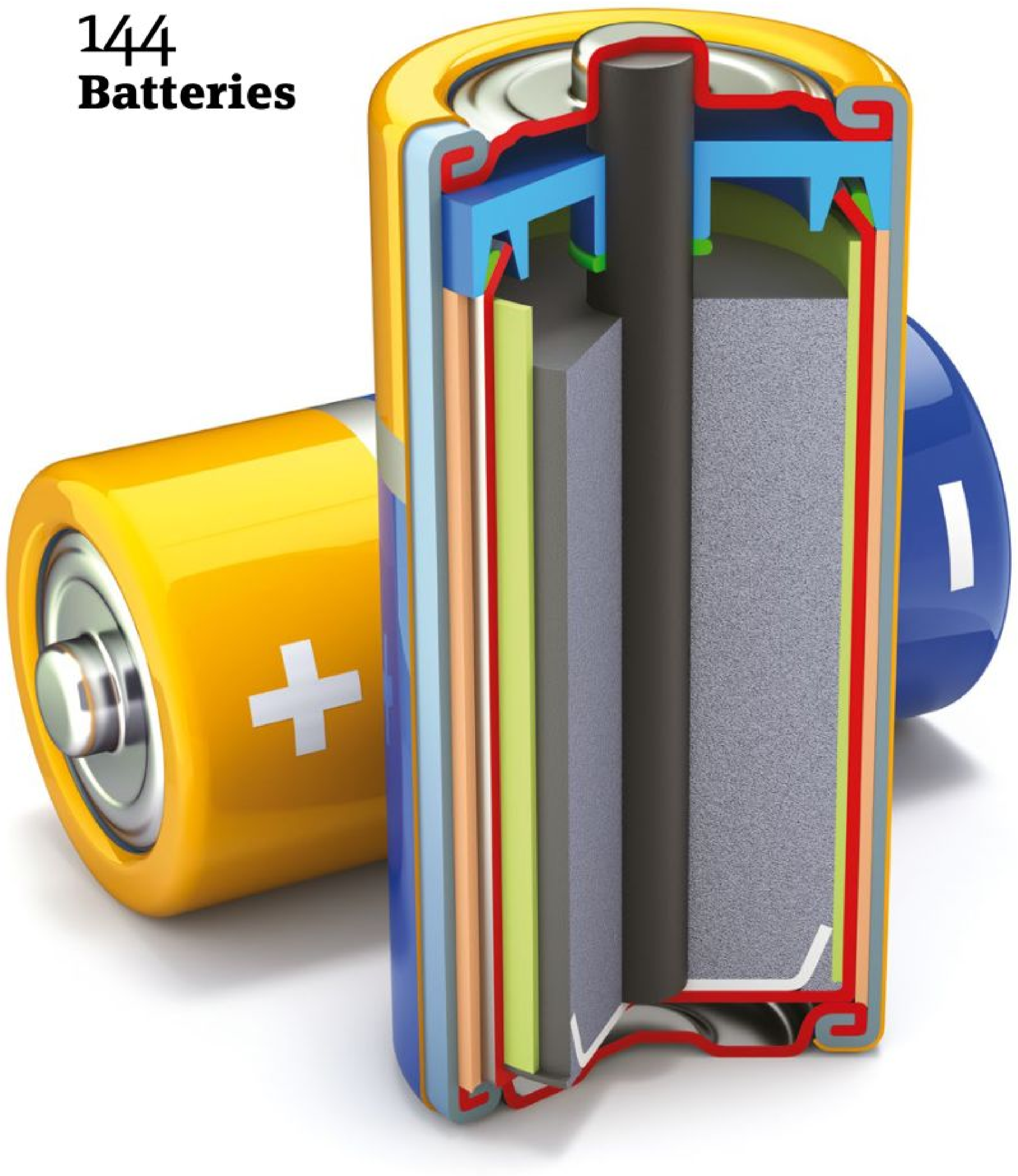
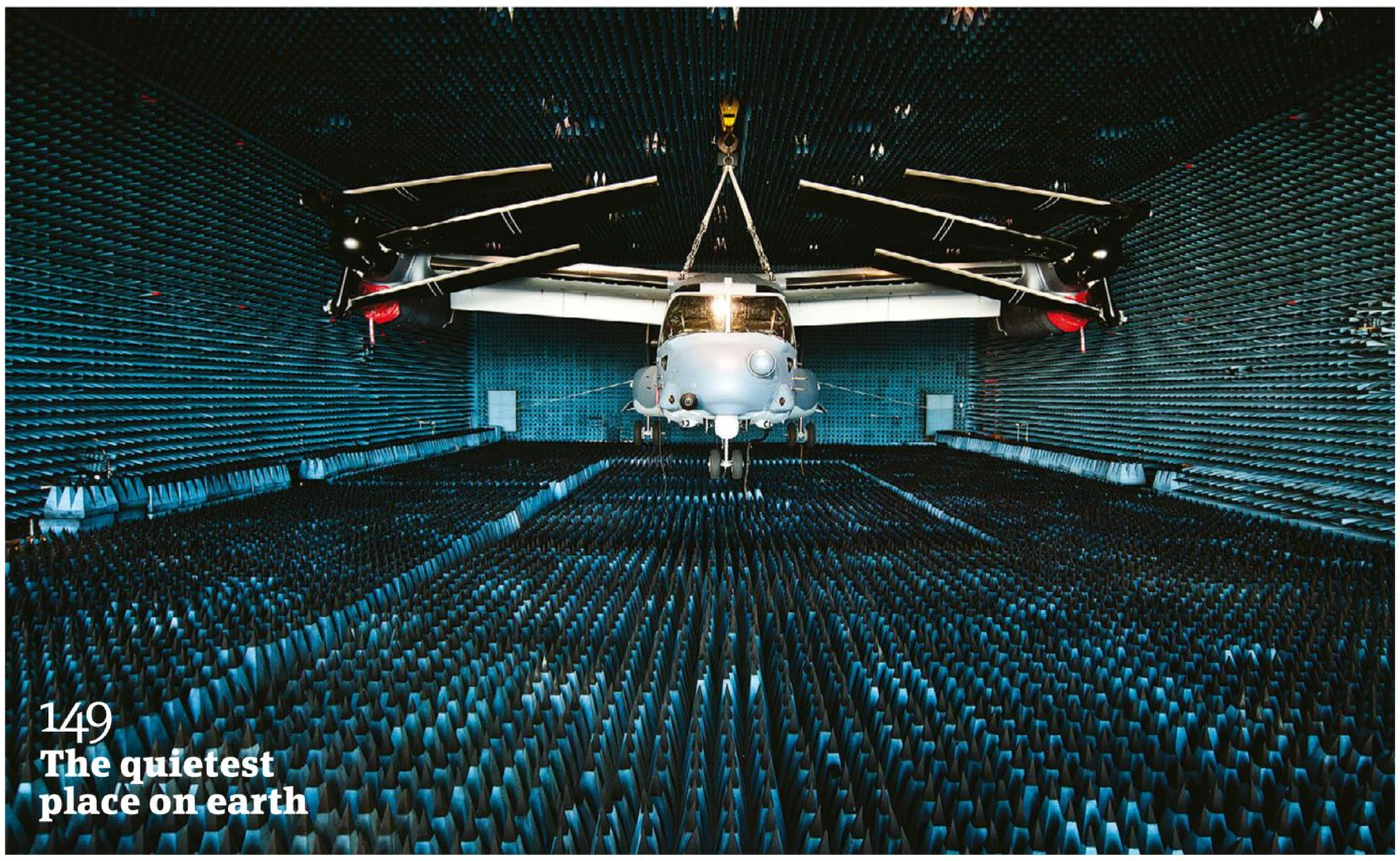
60 second science



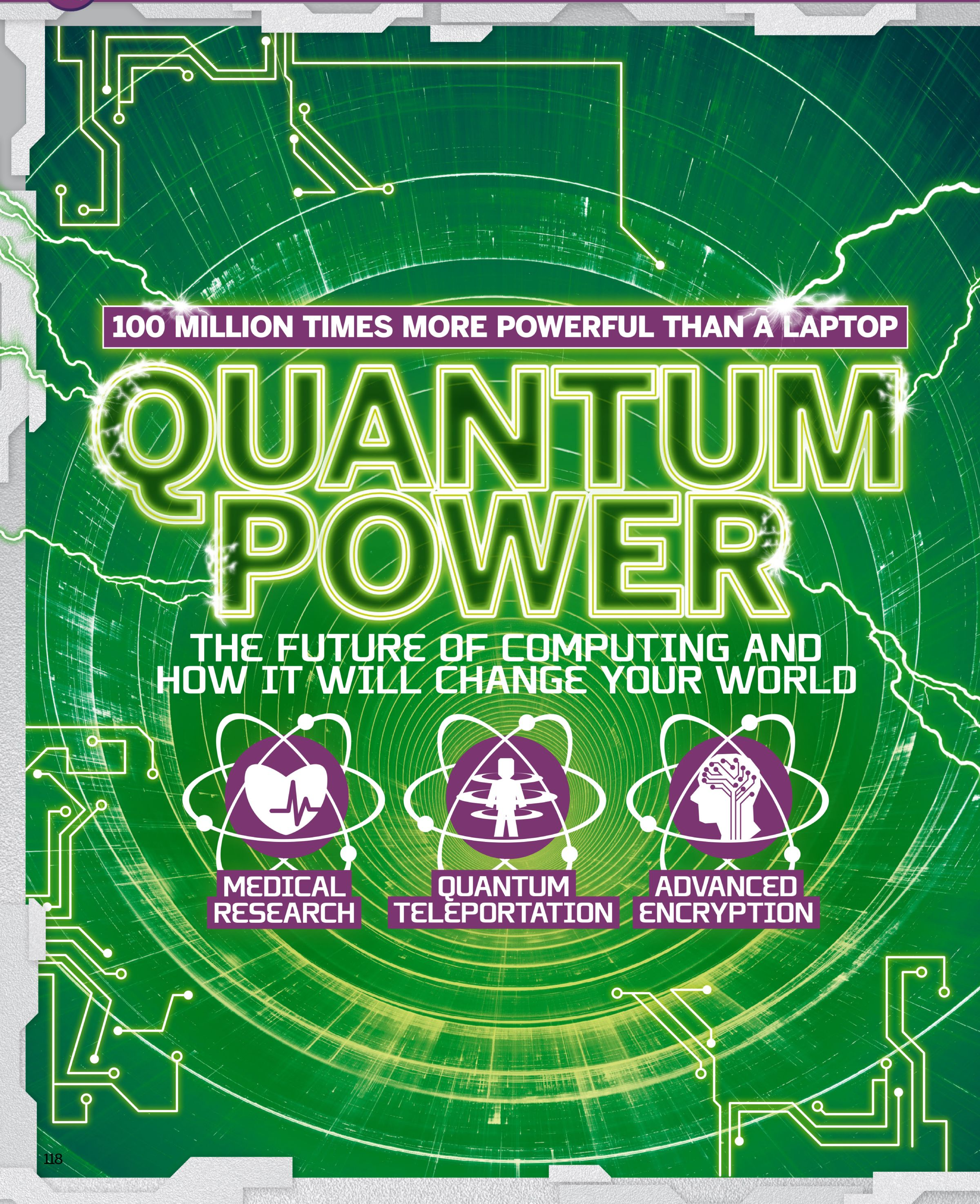
150
Nuclear power



144
Batteries



149
The quietest place on earth



100 MILLION TIMES MORE POWERFUL THAN A LAPTOP

QUANTUM POWER

THE FUTURE OF COMPUTING AND HOW IT WILL CHANGE YOUR WORLD

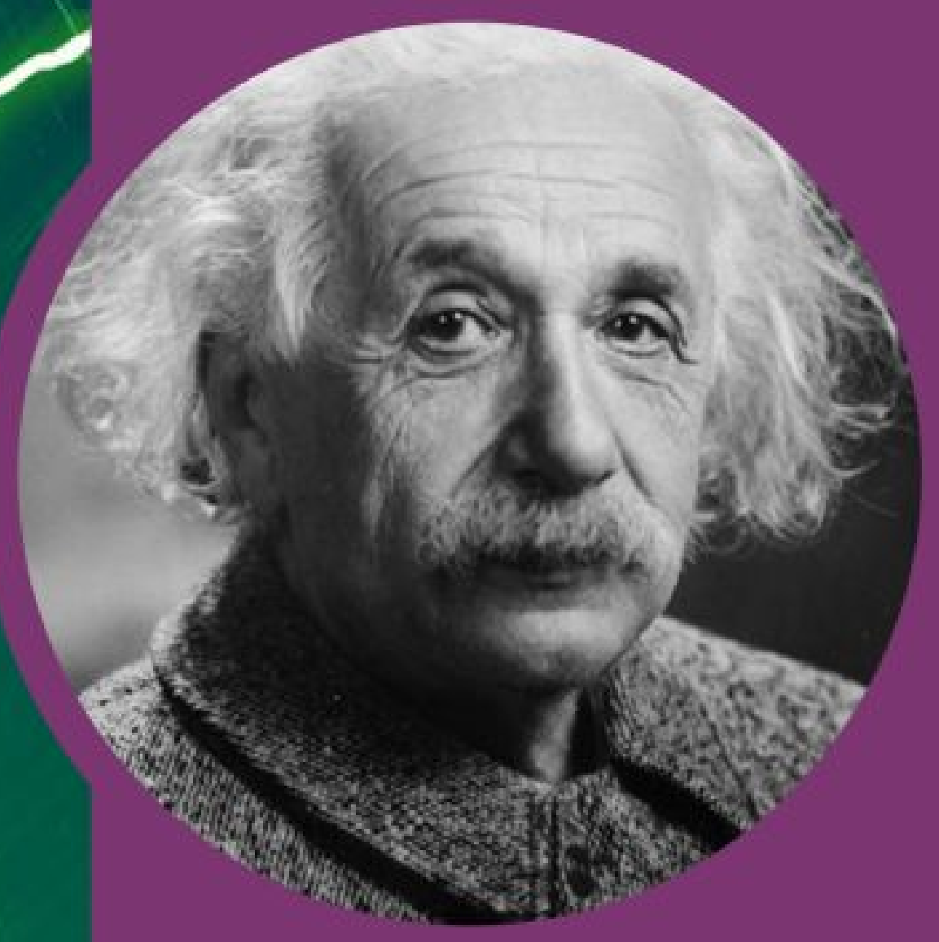
MEDICAL RESEARCH

QUANTUM TELEPORTATION

ADVANCED ENCRYPTION

The pioneers of quantum mechanics

Introducing the people who dared to think the unthinkable, laying the foundations of quantum technology



Albert Einstein
1905

Einstein explained the photoelectric effect by suggesting that light took the form of discrete bundles called photons. This seemed at odds with light's wave nature.

Louis de Broglie
1923

French physicist Louis de Broglie expanded on previous discoveries by proposing that all tiny particles can behave as waves, and vice versa.

Erwin Schrödinger
1926

Austrian physicist Erwin Schrödinger's paper describing the motion of an electron as a wave function was a defining moment in quantum mechanics.

Werner Heisenberg
1925-1927

Alongside Niels Bohr, Werner Heisenberg suggested that subatomic particles only adopt a particular state when observed.

Alexander Holevo
1973

Russian mathematician Alexander Holevo was one of several researchers to lay down the theoretical foundations of quantum mechanics.

It might be a term that trips off the tongue, and it may suggest a field of study dominated by the scientific elite, but quantum mechanics – or quantum physics if you prefer – is largely a mystery to the layperson. Surprisingly, therefore, it couldn't be much simpler to sum it up, even though understanding it is considerably more difficult.

Quantum mechanics is concerned with the behaviour of atoms, photons and the various subatomic particles, and it contrasts with classical physics, which describes the behaviour of everyday objects that are large enough to see.

The difference between classical physics and quantum mechanics is absolutely staggering. The objects that we see in the world around us behave in a way that seems intuitive, but once we start to consider very small objects, intuition and common sense have to be abandoned.

Instead, when we consider them individually, atoms, electrons and photons behave in a way that most people would be inclined to describe as impossible. That perception of impossibility isn't a naive view either. Even the eminent Nobel Prize-winning physicist Niels Bohr is on record as saying "If anybody says he can think about quantum theory without getting giddy, it merely shows that he hasn't understood the first thing about it."

We'll look at some of these concepts in more detail in the boxout below, but, having made such an astonishing claim, it's surely only appropriate to provide a couple of examples of apparently impossible quantum behaviour.

Perhaps one of the most bizarre things that can happen in the subatomic realm is that objects such as electrons or photons can be in two places at the same time or in two different states at once – a so-called state of superposition.

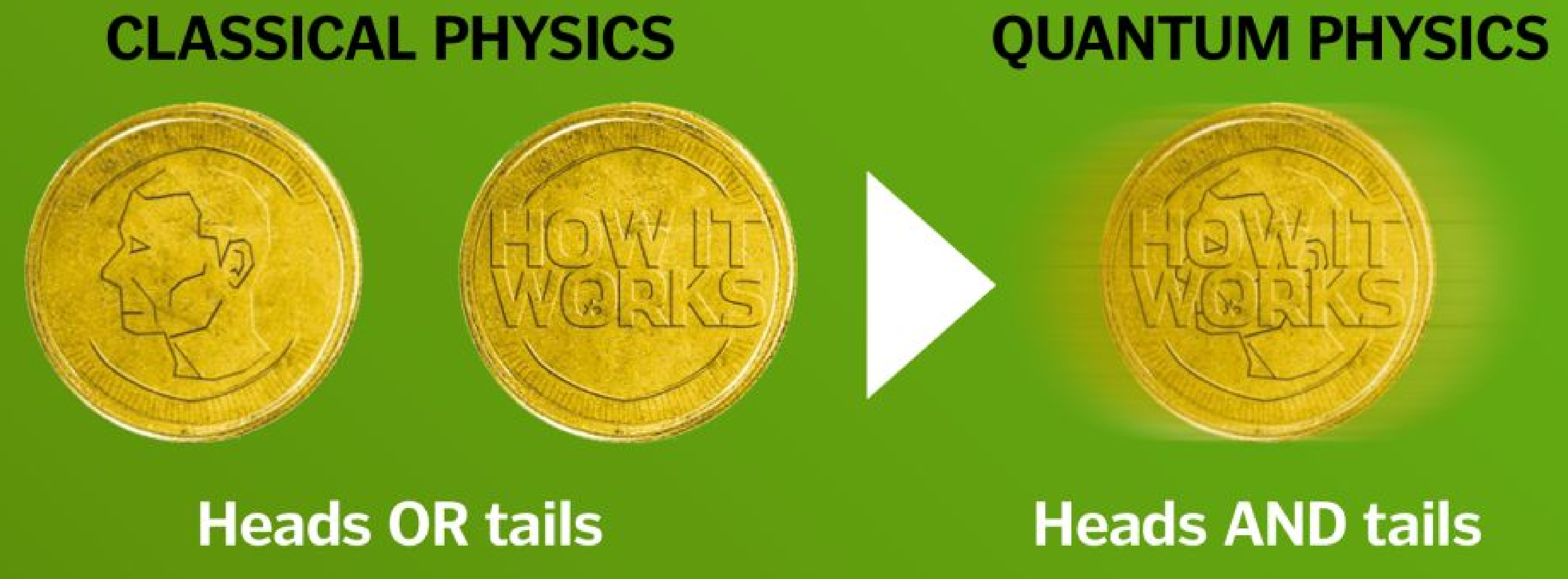
> "The difference between classical physics and quantum mechanics is absolutely staggering"

Quantum concepts

Examining the bizarre quantum effects that underpin quantum technology

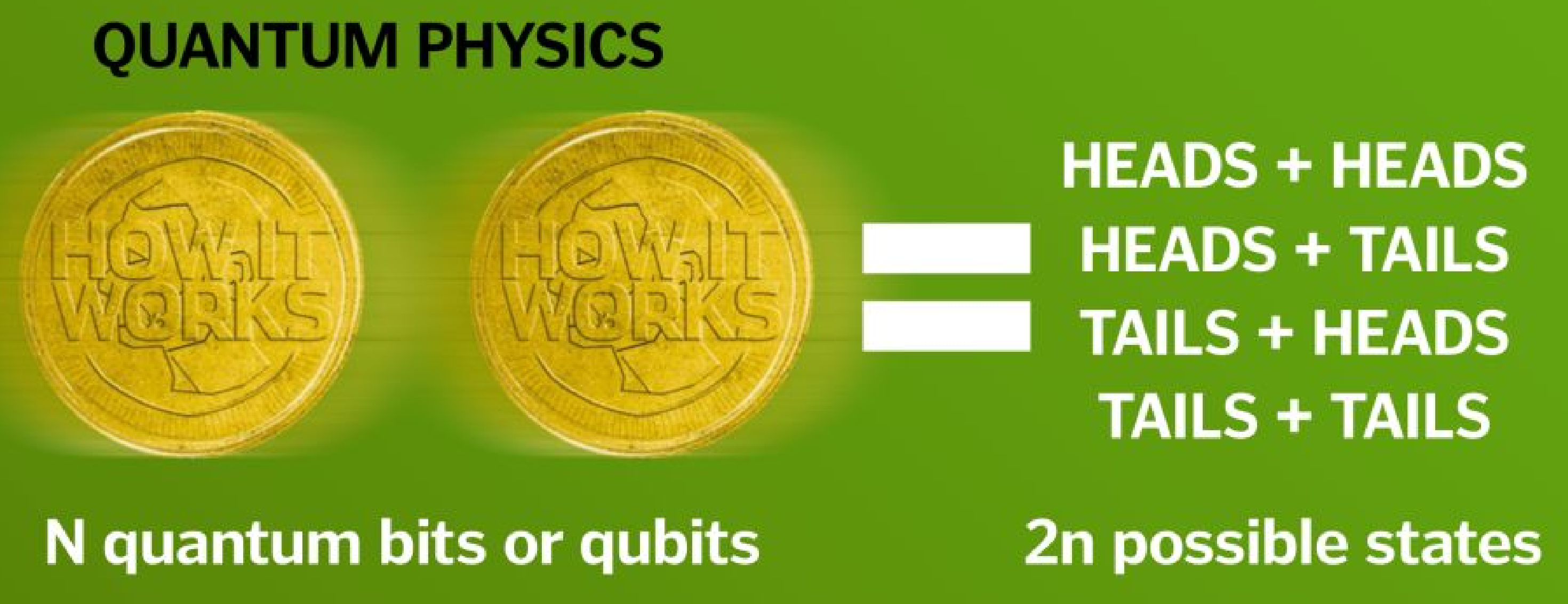
Superposition

A particle in superposition is in two states at once, so it could represent both a binary 0 and 1. Think of a coin: if it's spinning you can see heads and tails simultaneously.



Entanglement

Two entangled particles are strangely linked, so the fate of one affects the other. If you observe one particle this will cause its superposition to be lost, and the same will happen to its entangled twin.

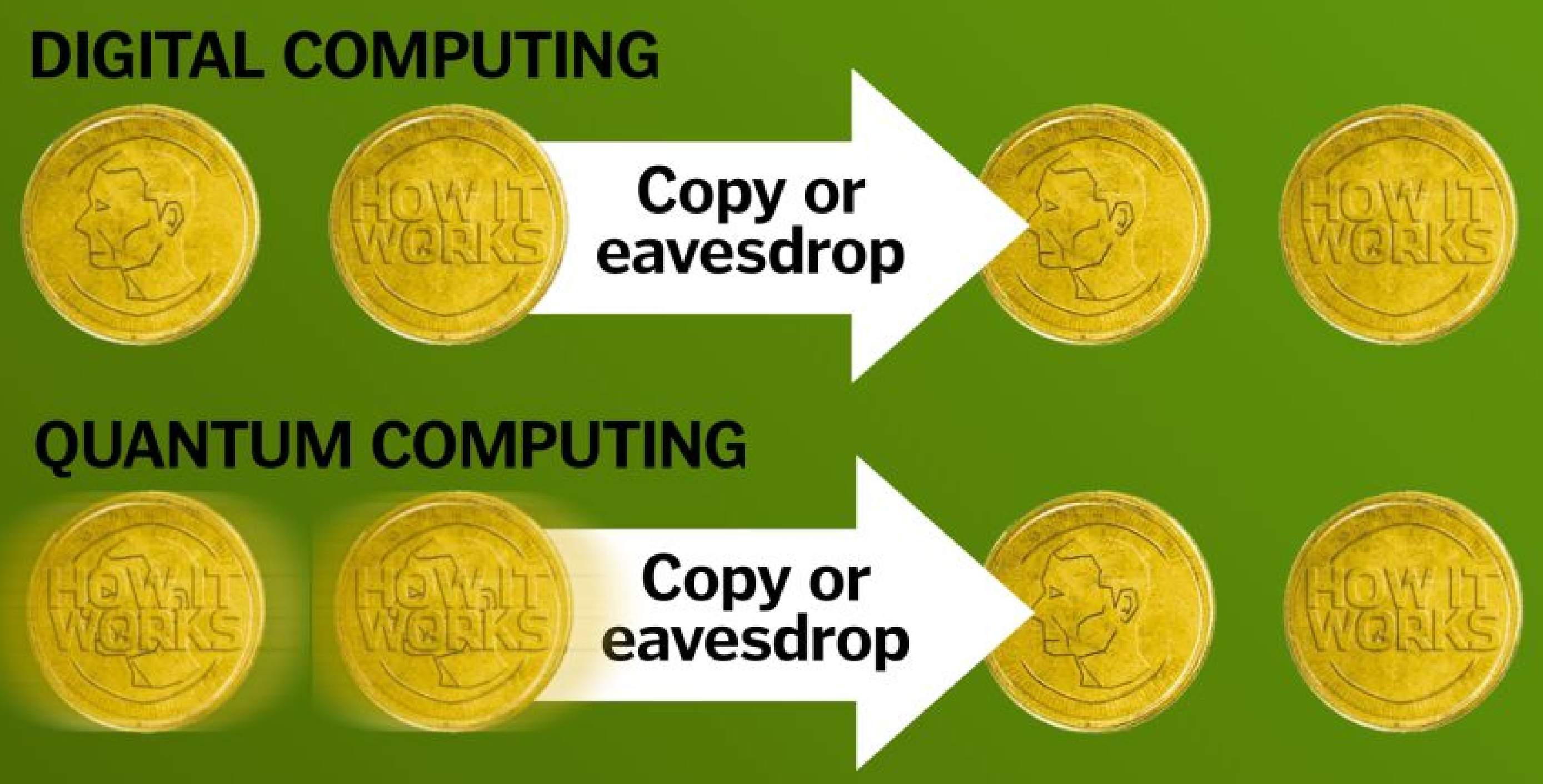


Observation

Observing a particle in superposition causes it to adopt a single state. Any interaction with the environment does the same. The more entangled the particles, the harder it is to maintain superposition.

No cloning

Making a copy of a particle in superposition also causes the superposition to be lost. This makes designing a quantum computer tricky, but, in quantum communications, it alerts the sender to the presence of an eavesdropper.



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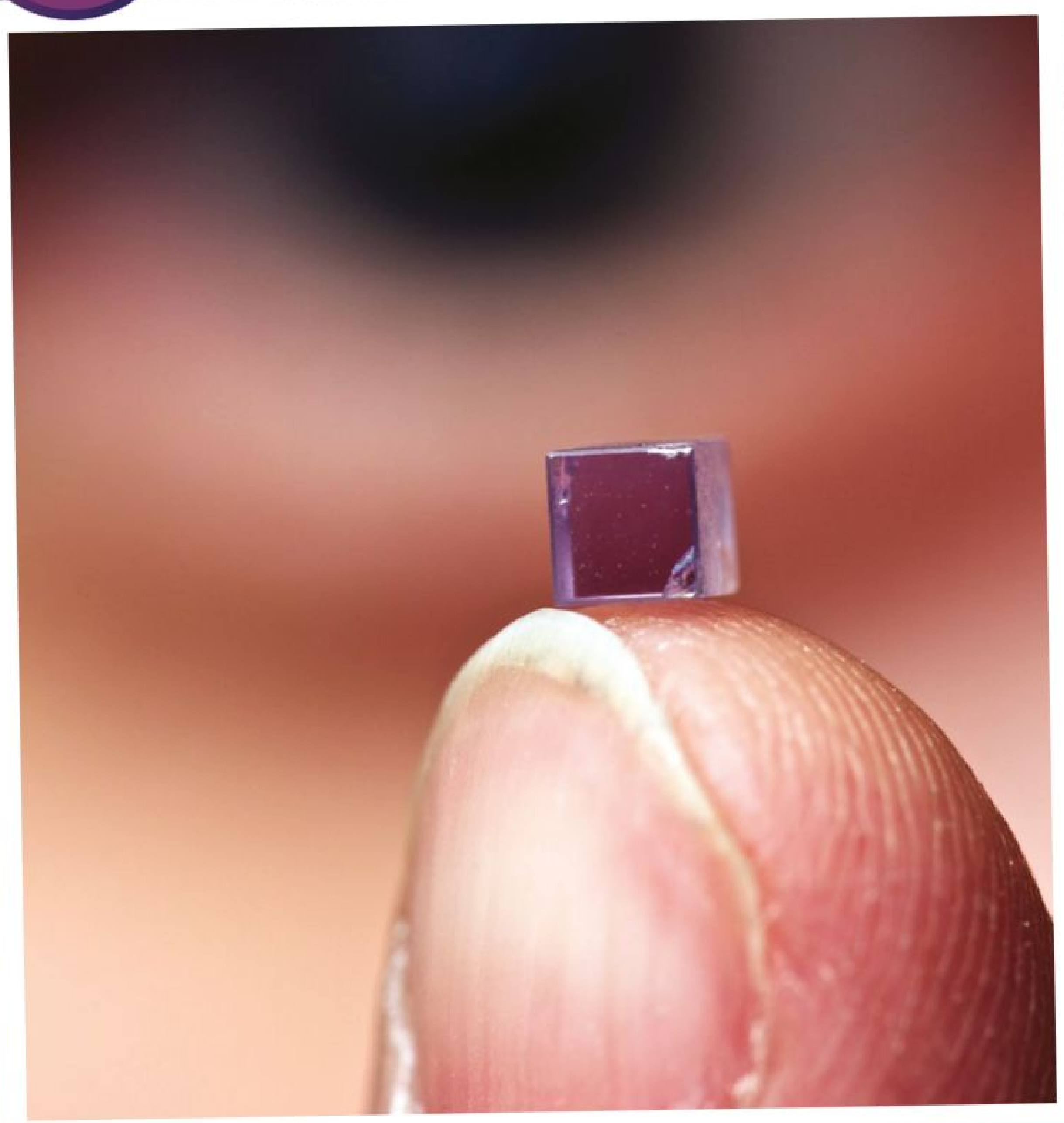
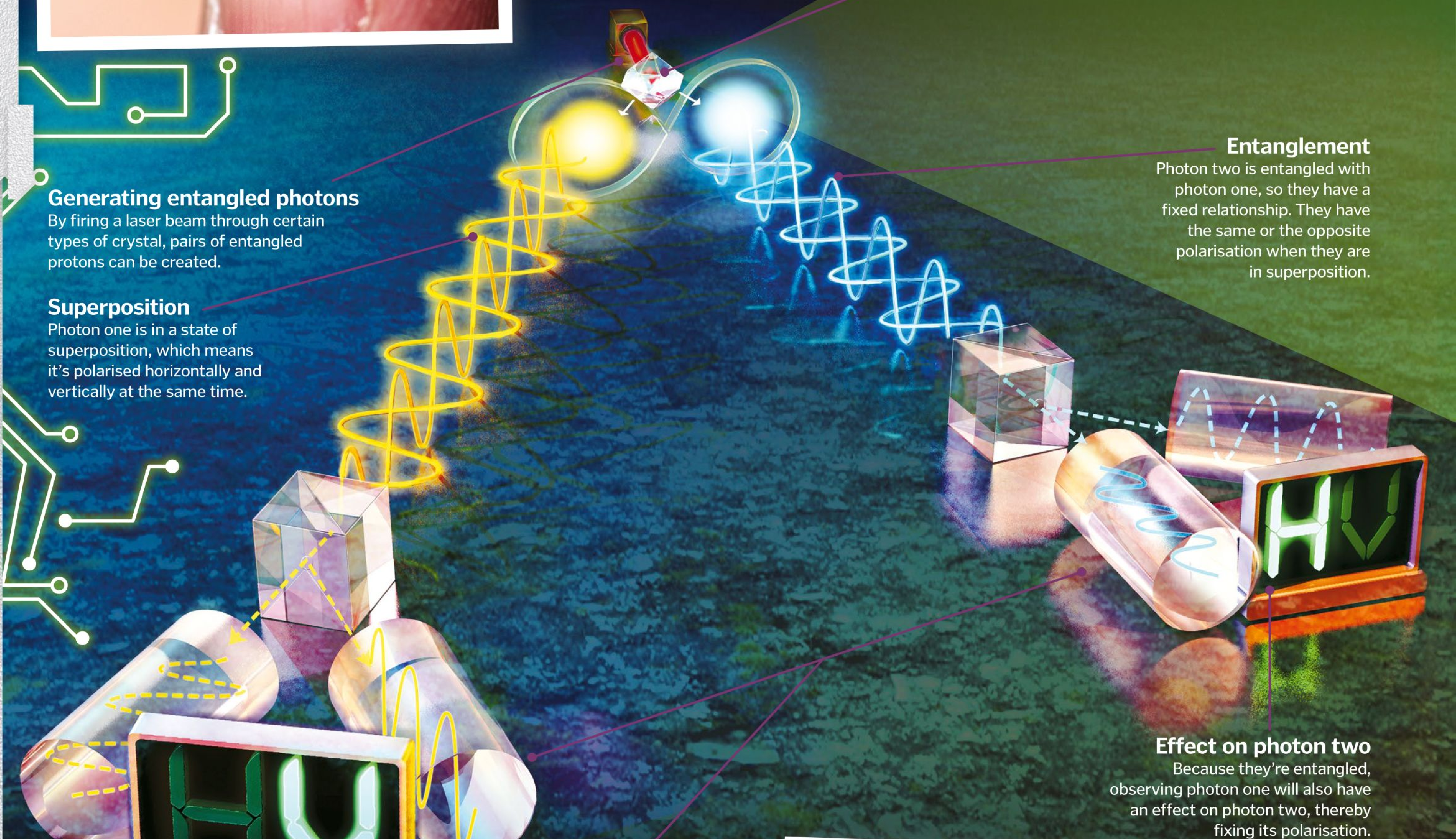
Understanding quantum entanglement

Experiments have confirmed a quantum effect that Einstein called "spooky"



Crystals doped with the rare element neodymium could potentially store quantum memories



Splitting the beam
In this experiment a beam-splitter is used so that the two photons are dispatched to different destinations.

Generating entangled photons
By firing a laser beam through certain types of crystal, pairs of entangled protons can be created.

Entanglement
Photon two is entangled with photon one, so they have a fixed relationship. They have the same or the opposite polarisation when they are in superposition.

Superposition
Photon one is in a state of superposition, which means it's polarised horizontally and vertically at the same time.

Effect on photon two
Because they're entangled, observing photon one will also have an effect on photon two, thereby fixing its polarisation.

Action at a distance
Observing one photon affects its entangled twin instantaneously, no matter how far apart the two photons are.

Observing photon one
When photon one is observed, superposition is lost and it will appear to be either horizontally (H) or vertically (V) polarised.

A scientist at the University of Geneva in Switzerland uses a laser to create entangled photons in researching quantum memory

You'll never be able to observe this odd state of affairs because, as soon as you try to do so, that object will appear to be in just the one place or one state. However, scientists have conducted cunningly-devised experiments that have confirmed that this peculiar behaviour really does happen, despite indications to the contrary whenever we try to observe it.

Another strange effect is called quantum mechanical tunnelling, and it refers to the fact that a tiny object is capable of passing straight through a solid barrier without damaging it. So, for example, if you fire an electron at a sheet of gold foil, there's a possibility that it could appear at the other side with the foil still intact.

The fact that particles can be in two places at once, and that they can pass through solid objects, both stem from the dual nature of tiny objects. At one time light was thought of as a wave, but later it was discovered that it could be described as a stream of particles called photons. Conversely, electrons were once considered as miniature particles that orbited an atom's nucleus like planets orbiting a sun, but subsequently it was discovered that they could be described as wave functions.

In reality, electrons and photons each have the properties of both particles and waves, or, in other words, both concepts are correct. So, that strange phenomenon in which an electron can be in two places at once is a consequence of the wave nature of electrons.

Instead of that now outdated view of orbiting electrons, wave theory concerns a so-called probability function. In other words, it describes the probability of the electron being at any particular point in space and, until the electron is observed, its position can be thought of as all points in space, albeit with some places being more likely than others.

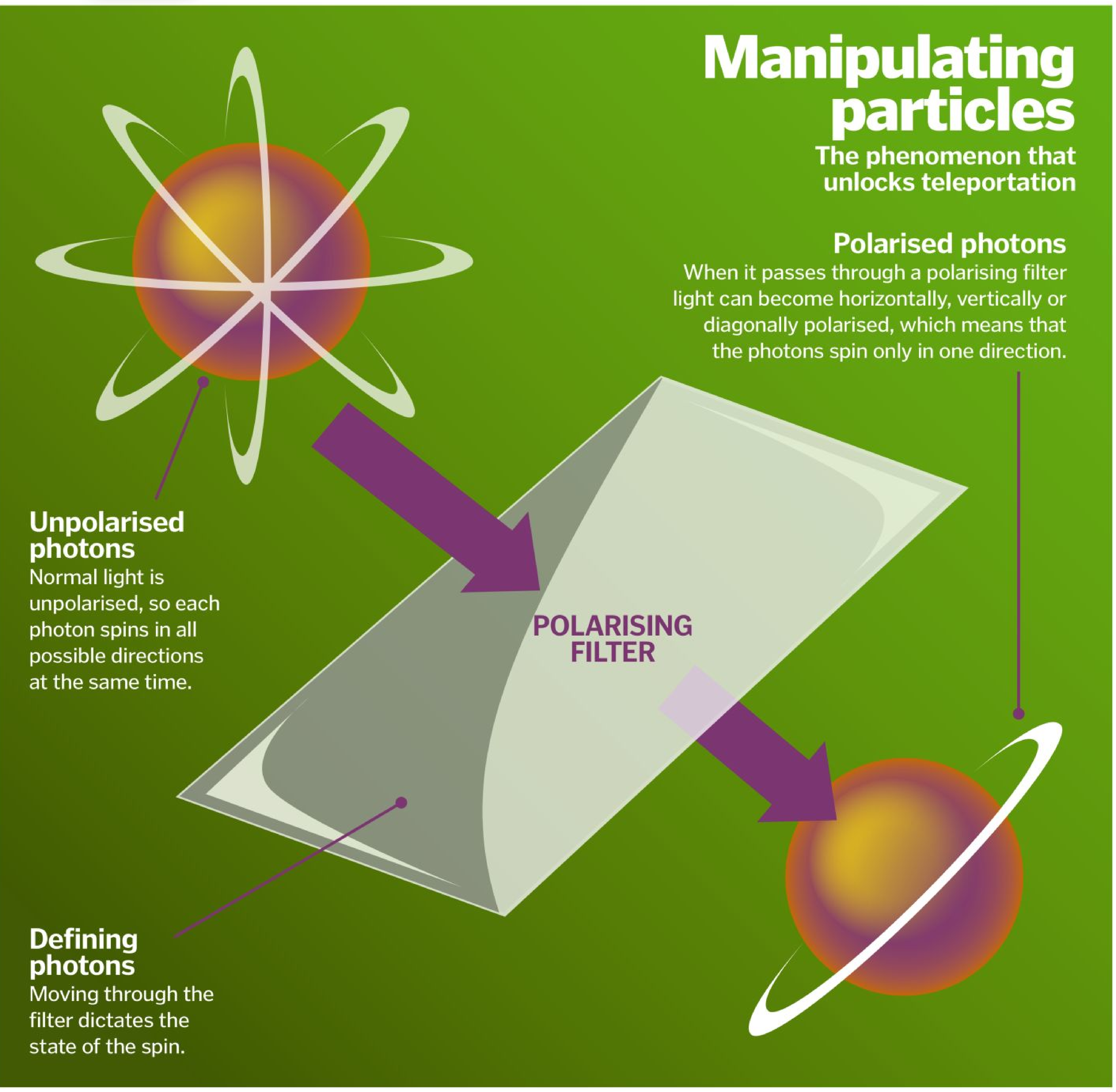
What we've seen so far has been known since the early 20th century, and it's strange enough. So any hope of ordinary people understanding the more recent developments in quantum theory is a forlorn one. However, to illustrate just how bizarre current thinking can be, let's think briefly about the multiverse theory, although even this dates back to the 1960s and 1970s.

You'll recall that observing a particle in a state of superposition causes its previously unknown position or state to become fixed. In the science-fiction-sounding multiverse theory, as soon as that observation takes place, the universe splits into two or more parallel universes, with that

> "Scientists have now taken their first steps in quantum teleportation"

Manipulating particles

The phenomenon that unlocks teleportation



Polarised photons
When it passes through a polarising filter light can become horizontally, vertically or diagonally polarised, which means that the photons spin only in one direction.

Unpolarised photons
Normal light is unpolarised, so each photon spins in all possible directions at the same time.

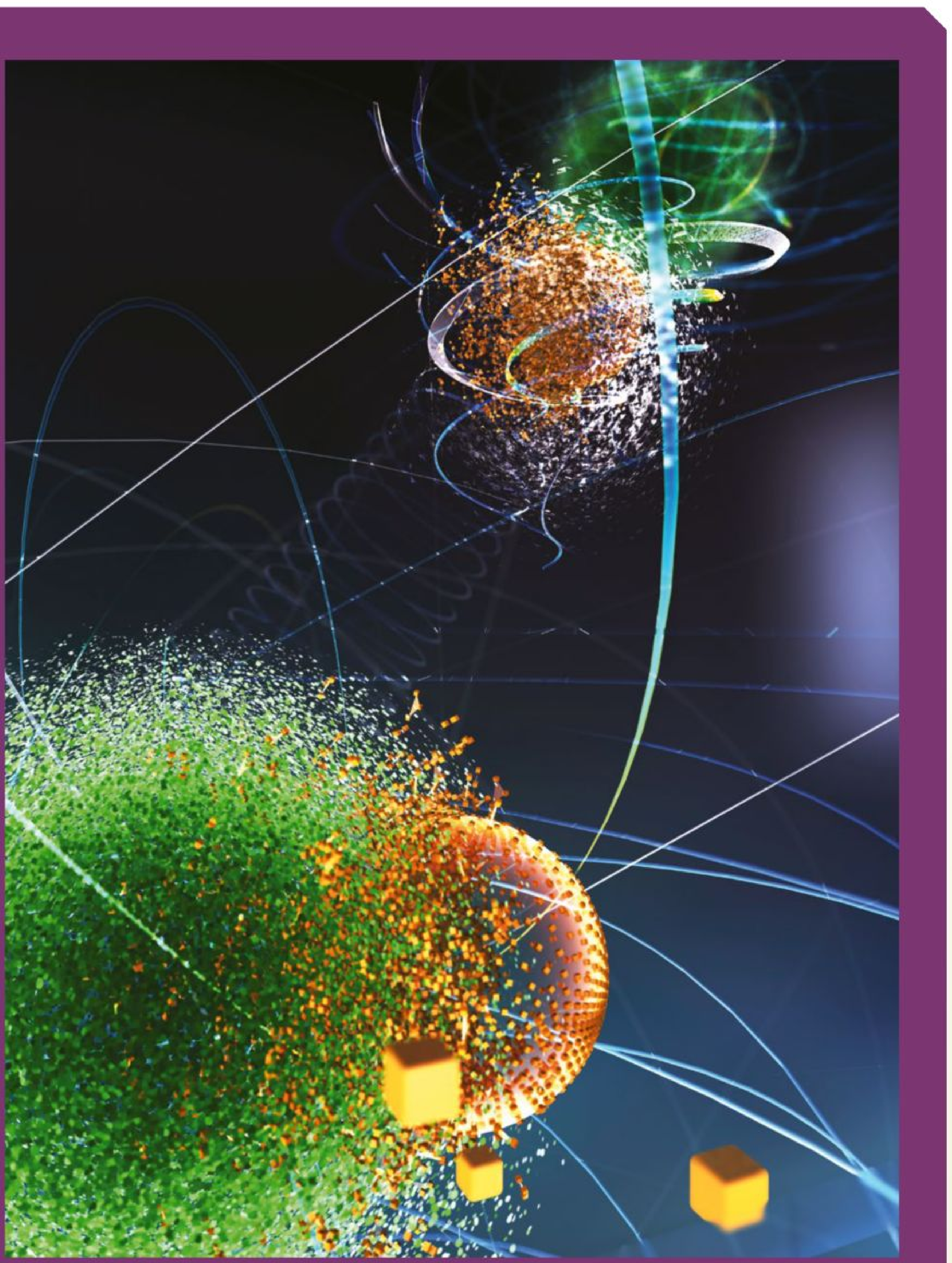
Defining photons
Moving through the filter dictates the state of the spin.

Quantum teleportation

We might be a considerable way from teleporting people, but single atoms and photons have already been teleported thanks to the use of quantum techniques.

The process involves creating two entangled particles at place A and then sending one of them to place B. Now, using clever techniques that also involve introducing a third particle that interacts with particle A, entanglement causes the particle at B to become an exact copy of the third particle. In reality, the actual particle hasn't moved, but the result is the same, so, effectively, the third particle has teleported to B's location instantly.

As with all things quantum, in practice this is incredibly difficult, and scientists are in a race to beat distance records. While the current record is 143 kilometres using a laser beam in September 2016, researchers in Calgary, Canada, and Shanghai, China, demonstrated quantum teleportation using a more practical fibre optic network to teleport photons across their respective cities.



Atoms and photons can now be teleported over ever-increasing distances

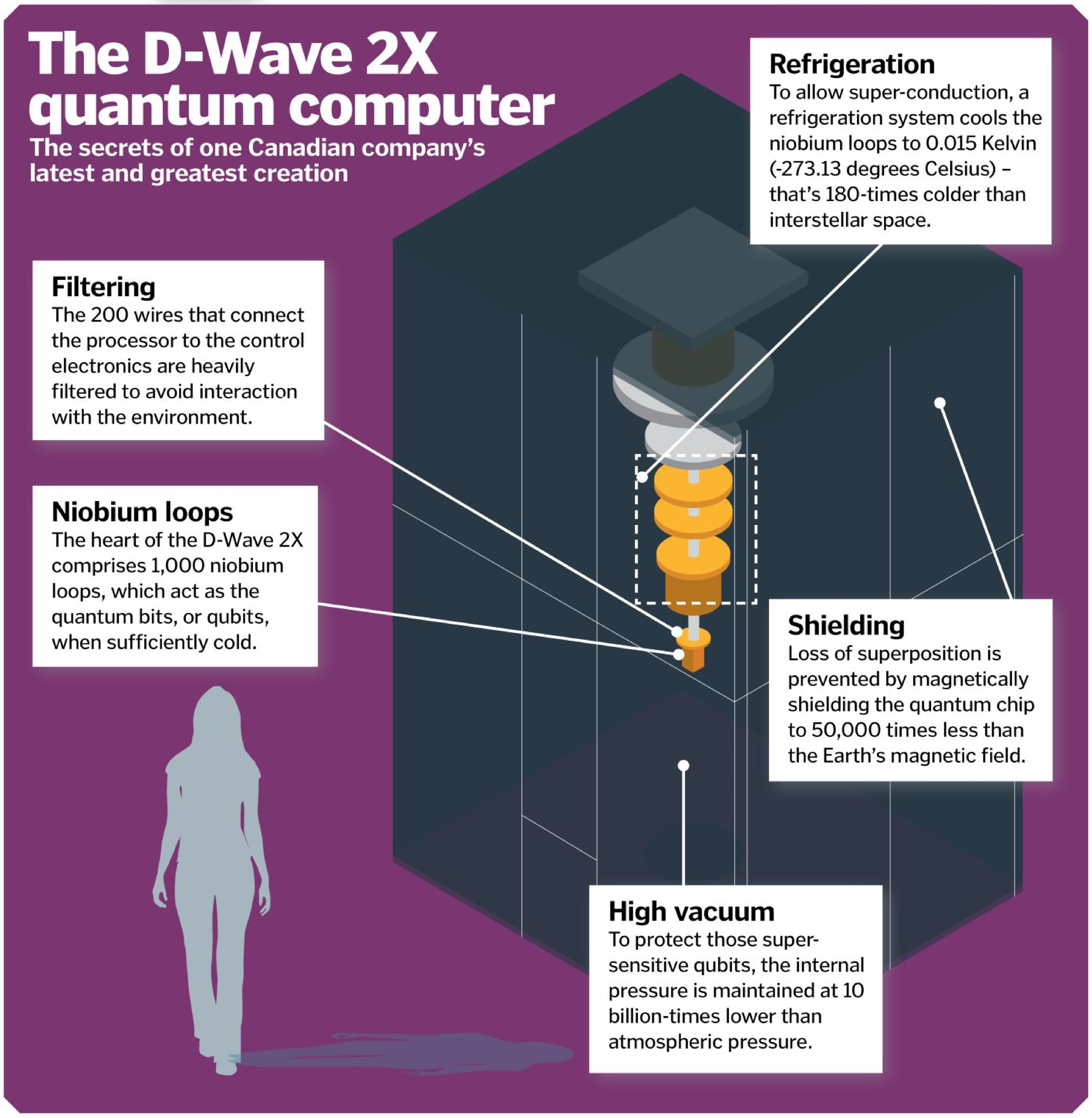
© SPL

particle being in a different location or state in each version of reality. What's more, with vast numbers of these splits taking place each second, that soon gives us an unimaginable number of parallel universes. This theory has gained additional credence recently as scientists have started to consider quantum computers. As we'll see later, compared to today's devices, if large-scale quantum computers ever become a reality, the performance they will offer will be absolutely astonishing.

This has led some scientists to suggest that there isn't enough material in the observable universe to carry out such a phenomenal number of computations. In the multiverse theory, however, that work is effectively farmed out into all of those parallel universes.

Given its very theoretical foundations, some people might be excused for thinking that quantum mechanics is an entertaining curiosity for scientists, but of absolutely no practical use. But experience has proven that most theoretical studies impact the real world eventually, and there's every indication that the same is true of studies in the quantum realm. Quantum mechanics has already given birth to many technological breakthroughs, and there are tantalising glimpses of what may lie ahead.

For a start, today's solid-state devices, which impact so much of 21st century life, depend on quantum effects. Most importantly, perhaps, is the transistor, which is the fundamental building block of computers, smartphones and pretty much all electronic devices. Another important solid-state device is the LED and the



The D-Wave 2X quantum computer

The secrets of one Canadian company's latest and greatest creation

Refrigeration
To allow super-conduction, a refrigeration system cools the niobium loops to 0.015 Kelvin (-273.13 degrees Celsius) – that's 180-times colder than interstellar space.

Filtering
The 200 wires that connect the processor to the control electronics are heavily filtered to avoid interaction with the environment.

Niobium loops
The heart of the D-Wave 2X comprises 1,000 niobium loops, which act as the quantum bits, or qubits, when sufficiently cold.

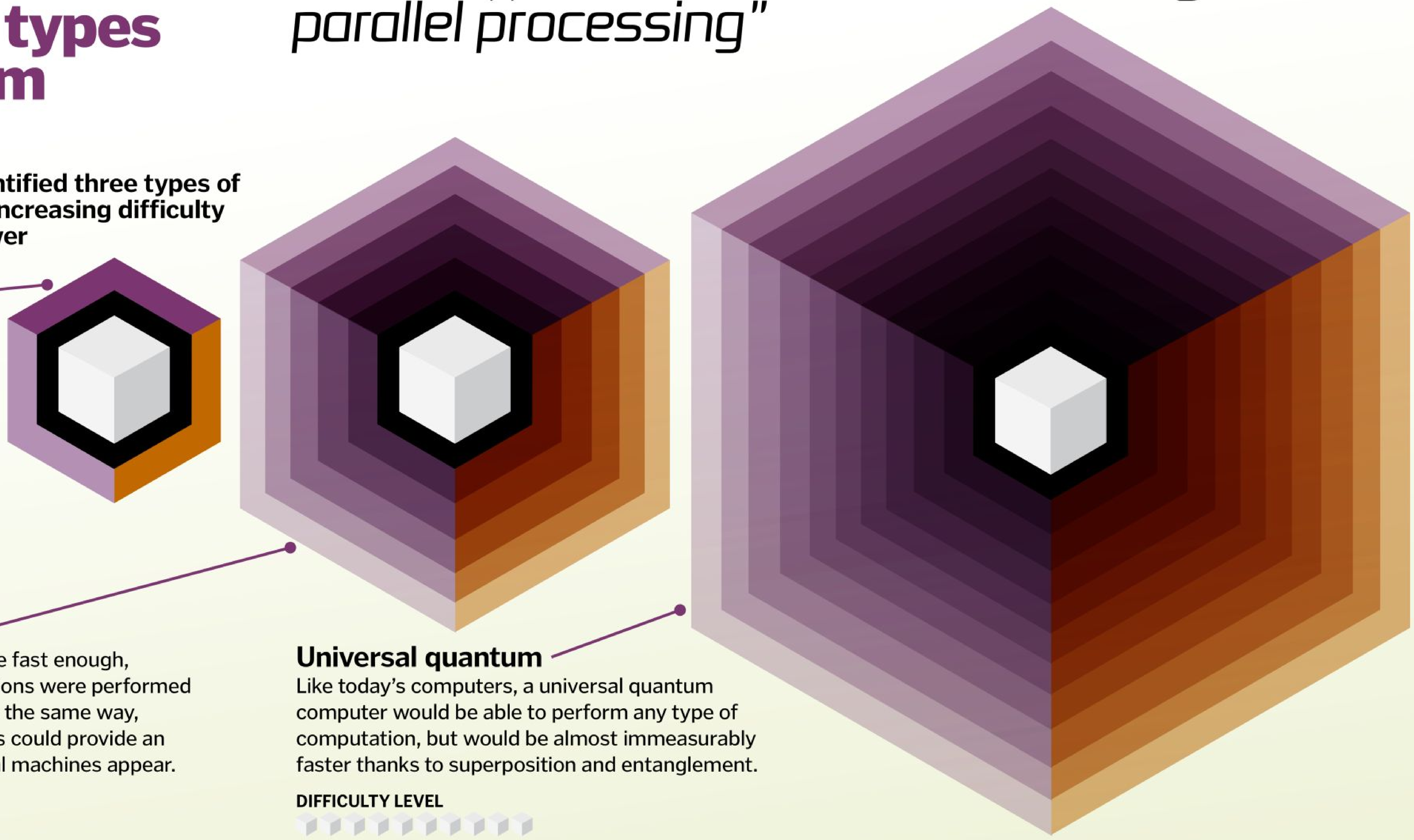
Shielding
Loss of superposition is prevented by magnetically shielding the quantum chip to 50,000 times less than the Earth's magnetic field.

High vacuum
To protect those super-sensitive qubits, the internal pressure is maintained at 10 billion-times lower than atmospheric pressure.

> *"A universal quantum computer would offer the ultimate in massively parallel processing"*

The three types of quantum computer

IBM Research have identified three types of quantum computer of increasing difficulty but also increasing power



Quantum annealer
Today's only commercial quantum computer is a quantum annealer. This is a specialised architecture that is designed for a whole range of applications that are described as optimisation tasks.

DIFFICULTY LEVEL
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Analogue quantum
Before digital computers were fast enough, high-speed scientific calculations were performed using analogue computers. In the same way, quantum analogue computers could provide an interim solution until universal machines appear.

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Universal quantum
Like today's computers, a universal quantum computer would be able to perform any type of computation, but would be almost immeasurably faster thanks to superposition and entanglement.

DIFFICULTY LEVEL
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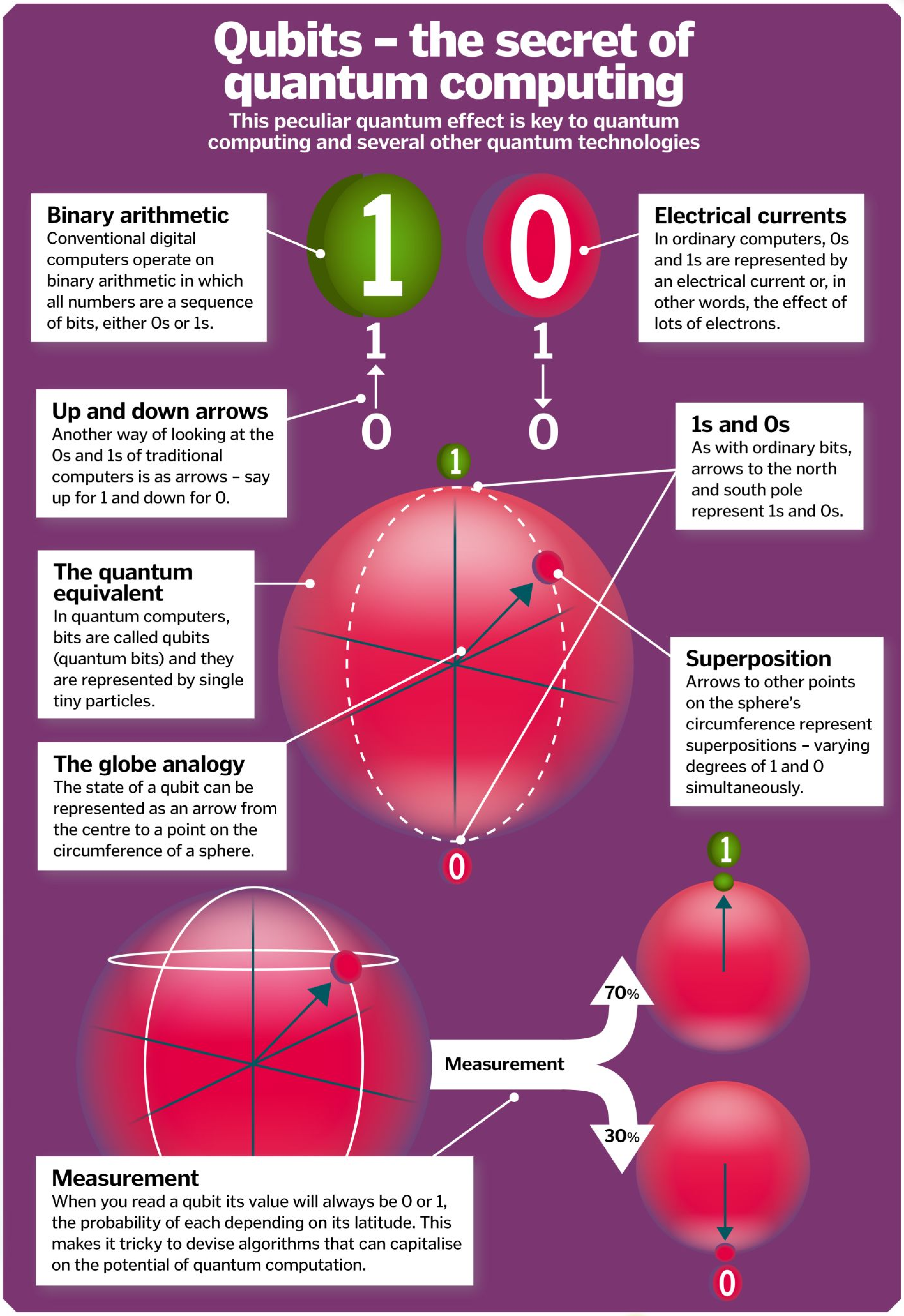
closely related solid-state laser. The former is now revolutionising lighting by bringing hitherto unprecedented levels of energy efficiency, while the latter is key to the fibre optic cables that span the globe empowering the internet, and is also a vital component in CD and DVD drives.

Atomic clocks are also reliant on quantum mechanics, and these instruments provide the precision timing needed for the operation of GPS systems on which sat navs and smartphone navigation apps rely. Quantum mechanics also underlies the principles of magnetic resonance imaging (MRI) machines, which allow physicians to see inside the body.

Little was said about their quantum heritage when these various technologies were developed, but we're now starting to hear about several new technologies that are much more up front about their quantum roots. What's more, these up-and-coming applications of quantum mechanics are absolutely mind-blowing.

Thought that *Star Trek* style teleportation was the result of an over-active imagination? Think again – scientists have now taken their first steps in quantum teleportation. What about a code that is totally unbreakable? Experience tells us that however sophisticated a code, all it takes is a sufficiently powerful computer and encrypted

MRI scanners work using the principles of quantum mechanics



Qubits – the secret of quantum computing

This peculiar quantum effect is key to quantum computing and several other quantum technologies

Binary arithmetic
Conventional digital computers operate on binary arithmetic in which all numbers are a sequence of bits, either 0s or 1s.

Electrical currents
In ordinary computers, 0s and 1s are represented by an electrical current or, in other words, the effect of lots of electrons.

Up and down arrows
Another way of looking at the 0s and 1s of traditional computers is as arrows – say up for 1 and down for 0.

1s and 0s
As with ordinary bits, arrows to the north and south pole represent 1s and 0s.

The quantum equivalent
In quantum computers, bits are called qubits (quantum bits) and they are represented by single tiny particles.

Superposition
Arrows to other points on the sphere's circumference represent superpositions – varying degrees of 1 and 0 simultaneously.

The globe analogy
The state of a qubit can be represented as an arrow from the centre to a point on the circumference of a sphere.

Measurement
When you read a qubit its value will always be 0 or 1, the probability of each depending on its latitude. This makes it tricky to devise algorithms that can capitalise on the potential of quantum computation.

Quantum computers by numbers

100 million times
How much faster the D-Wave 2X is compared to an ordinary computer

2^1,000
Number of solutions the current D-Wave 2X quantum computer can search simultaneously

1,000
The greatest number of entangled qubits achieved

18.4 billion billion
How many calculations a universal 64-qubit quantum computer could do simultaneously

2^16
How many simultaneous searches the first 16-qubit D-Wave quantum computer could perform in 2007

100,000
Number of qubits needed for a practical universal quantum computer

© Illustration by Neo Phoenix; Thinkstock

messages can be accessed. Not so with quantum cryptography. This isn't a code that's so fiendishly difficult that it would take all the computers on the planet years to crack. This is a method of encryption that, according to the laws of quantum mechanics, is totally secure, however much computing power you throw at it. And then we have quantum computers and the world of opportunities it opens up.

For now, though, let's just say that one company is already selling a rather specialised quantum computer, and research continues into a quantum equivalent of today's PCs, a universal quantum computer. If these ever come to fruition, they won't just be incrementally faster than their predecessors, which have doubled in speed every couple of years or so. Instead, a truly universal quantum computer holds the promise of almost unlimited performance thanks to that strange quantum effect of superposition, coupled with the equally strange quantum effect of entanglement.

By being in millions upon billions of states at the same time, a universal quantum computer would offer the ultimate in massively parallel processing, in which multiple operations are carried out simultaneously.

It is widely acknowledged that last century was the era of electronics. Within a period of just 52 years the very first electronic device, the vacuum tube or valve, was invented, and this was superseded first by the transistor and then by the integrated circuit. It only took another 13 years for the first microprocessor to be released.

Renowned quantum physicist Professor Rainer Blatt has described the technological developments of the last century as the first quantum revolution, and with some justification. After all, many of the developments that underpin today's society resulted from an understanding of quantum mechanics and, in particular, wave-particle duality. Professor Blatt suggests that humanity now stands at the dawn of a second quantum revolution that will be empowered by the weird quantum effect of entanglement.

According to Professor Blatt, "In the early 1960s, the laser was still seen as a solution to an unknown problem, and today, just over 50 years later, lasers have become an indispensable part of our lives – I expect quantum technologies to develop along similar lines."

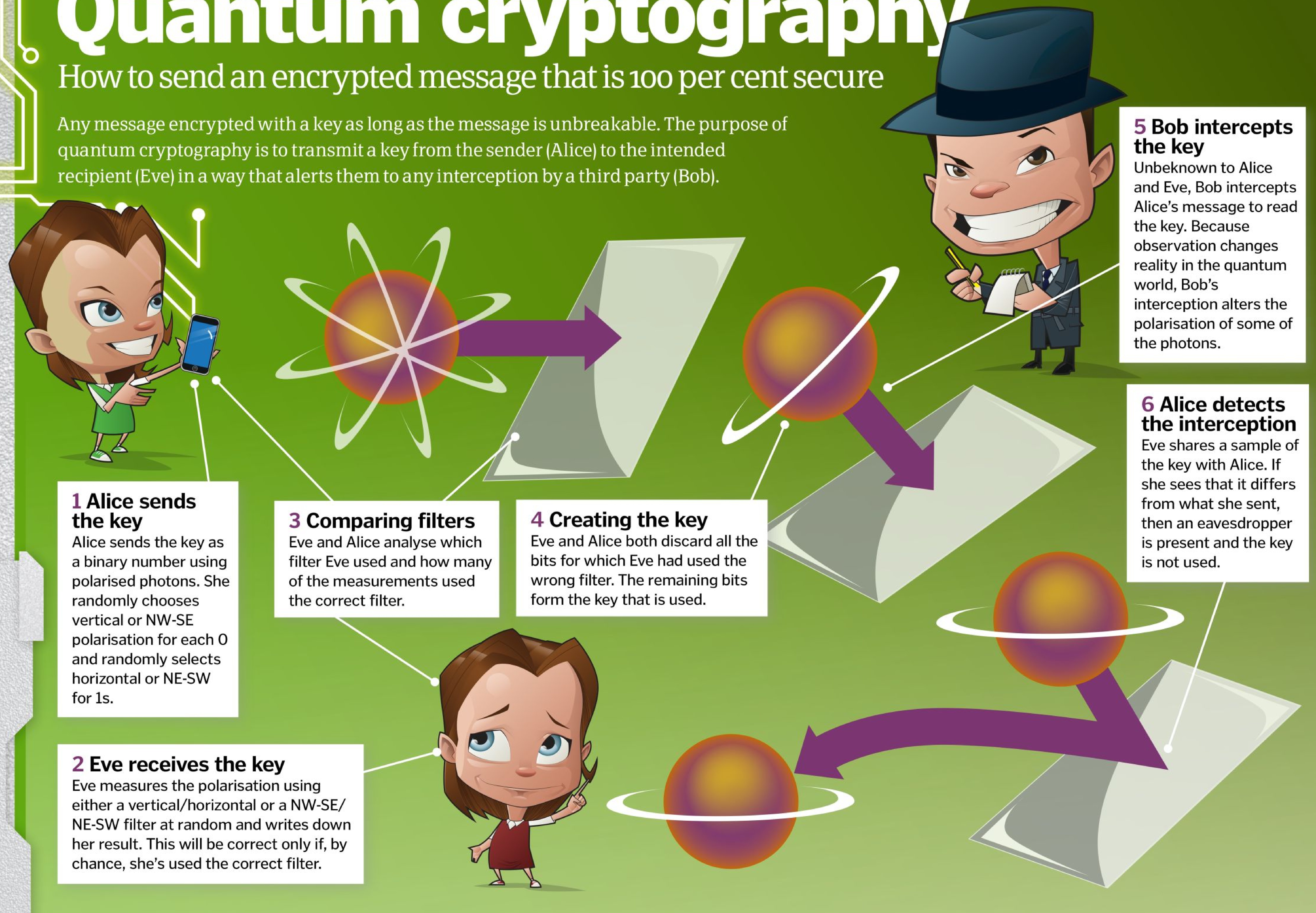
> "We now stand at the dawn of a second quantum revolution"

Quantum computing has a wide range of applications, from improving air-traffic control systems to creating better speech recognition software

Quantum cryptography

How to send an encrypted message that is 100 per cent secure

Any message encrypted with a key as long as the message is unbreakable. The purpose of quantum cryptography is to transmit a key from the sender (Alice) to the intended recipient (Eve) in a way that alerts them to any interception by a third party (Bob).



1 Alice sends the key

Alice sends the key as a binary number using polarised photons. She randomly chooses vertical or NW-SE polarisation for each 0 and randomly selects horizontal or NE-SW for 1s.

2 Eve receives the key

Eve measures the polarisation using either a vertical/horizontal or a NW-SE/NE-SW filter at random and writes down her result. This will be correct only if, by chance, she's used the correct filter.

3 Comparing filters

Eve and Alice analyse which filter Eve used and how many of the measurements used the correct filter.

4 Creating the key

Eve and Alice both discard all the bits for which Eve had used the wrong filter. The remaining bits form the key that is used.

5 Bob intercepts the key

Unbeknown to Alice and Eve, Bob intercepts Alice's message to read the key. Because observation changes reality in the quantum world, Bob's interception alters the polarisation of some of the photons.

6 Alice detects the interception

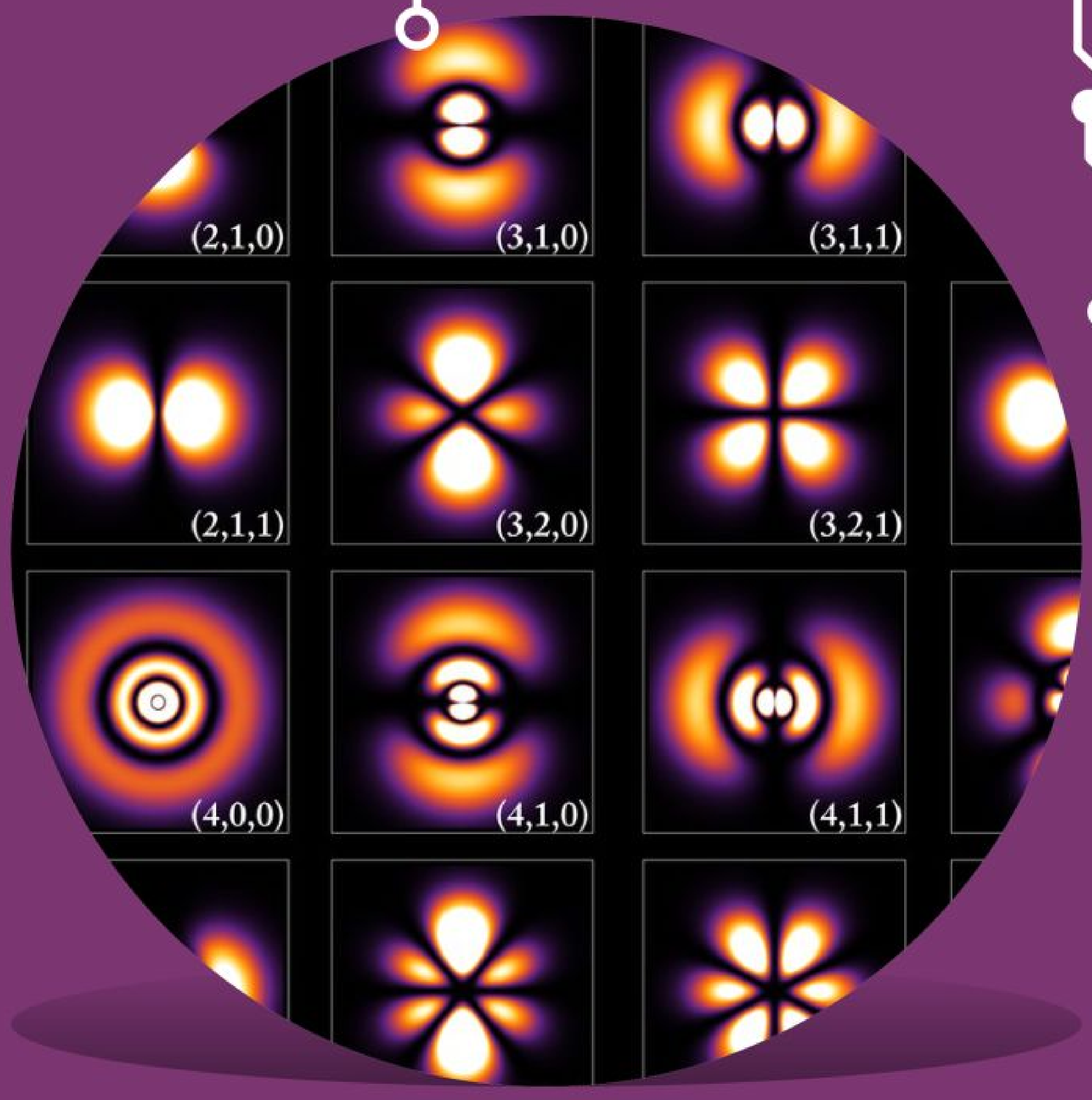
Eve shares a sample of the key with Alice. If she sees that it differs from what she sent, then an eavesdropper is present and the key is not used.

Applying quantum mechanics

In the future there may be numerous ways to use this rapidly growing technology

Image searching

Humans are easily able to detect familiar objects such as trees, lakes and cats when they look at a photograph. Teaching computers to do likewise is a really difficult programming task because it's so hard to define the essence of 'cat-ness', for example. But machine learning tasks like this are natural applications for quantum computers. Google has already invested considerable research effort into image analysis to make online picture searching more efficient. This was demonstrated by teaching a quantum computer to recognise cars in photos, a task it was then able to do much quicker than an ordinary computer could ever achieve.



Quantum simulation

It might seem like a circular argument but, just as an understanding of quantum mechanics has now given us quantum computers, scientists are now hoping that those same quantum computers will help them to better understand quantum systems by simulating them. Today's computers are able to carry out simulations of quantum effects but, such is the complexity of quantum systems, they are incredibly slow. It perhaps comes as no surprise, then, that computers that are based on the strange world of quantum mechanics are much more capable of simulating quantum systems and, thereby, help scientists to gain new insights.

Astronomy

Given that NASA jointly owns one of the world's first quantum computers, it's hardly surprising that astronomy will probably be one of the main beneficiaries of this new model of computation. The space agency has its sights set on several ways that quantum computing can assist in the exploration of space, but many of them can be summed up as searching through huge amounts of data for the proverbial needle in the haystack. A classic example is the search for habitable exoplanets; Earth-like planets in orbit at the ideal distance from faraway stars, that might just be capable of hosting life.

Radiotherapy optimisation

According to D-Wave Systems, their D-Wave 2X computer, working with a conventional computer, will help to optimise radiotherapy. This treatment aims to target a tumour while minimising harmful exposure to the rest of the body, with several beams intersecting at the tumour. Its optimisation involves juggling thousands of variables. To achieve it, simulations would be carried out on a huge number of possibilities using a conventional computer, while a quantum annealing computer would determine the most probable scenarios for simulation.

> "Encrypted messages would be an open book for a general-purpose quantum computer"

Code breaking

A universal quantum computer would be able to factor large numbers with ease, a phenomenally time-consuming job for conventional computers. Today's ciphers rely on the fact that factoring is difficult, but encrypted messages would be an open book once general-purpose quantum computers become reality. This might be useful to the military and police forces – for example, in the fight against terror and organised crime – but it would also be a boost to cyber criminals. It's quite appropriate that the same quantum technology that might make today's encryption techniques obsolete could provide a replacement in the form of quantum cryptography.

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The Large Hadron Collider

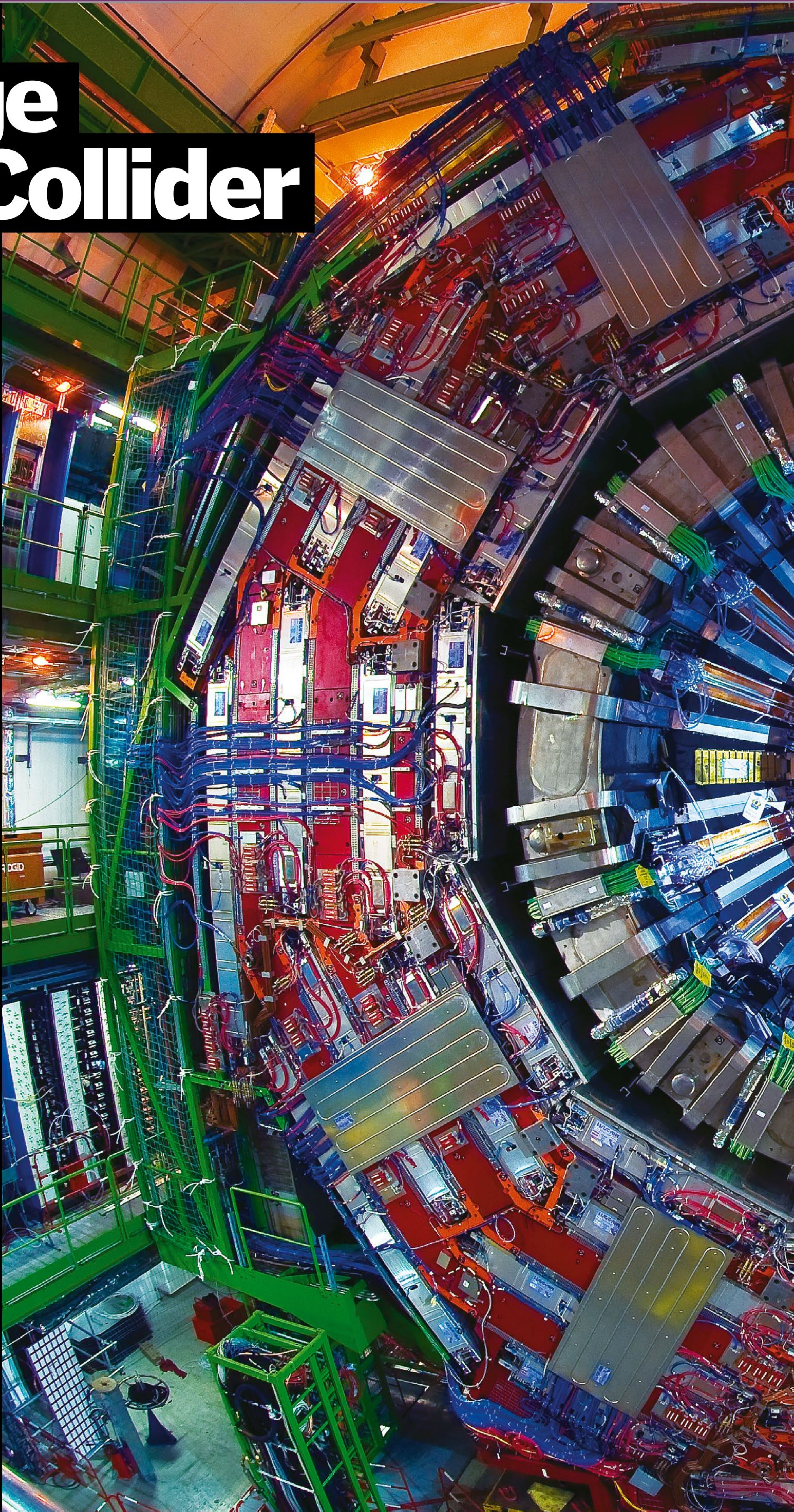
The huge machine helping scientists to uncover the structure of the universe

The Large Hadron Collider, or LHC, is a physics experiment on a phenomenal scale. The 27-kilometre tunnel is the world's largest particle accelerator, a powerful machine that could help us to understand the fundamental laws of nature. But although the setting is huge, the science is very small indeed; the LHC provides a peek inside the nucleus of an atom, which is made up of particles that are less than a trillionth of a millimetre across.

Inside the LHC, these subatomic particles, or protons, are fired at each other at high speed using electromagnets, producing millions of proton collisions per second. These are captured by sensitive detectors and give scientists an insight into the conditions that existed in the fraction of a second after the Big Bang.

The LHC is one of several particle accelerators belonging to the European Organization for Nuclear Research, or CERN. The accelerators are used in succession to boost the speed of the protons until they reach almost the speed of light. Many different projects are based at the accelerator complex at CERN, including the ATLAS and CMS experiments that resulted in the Higgs boson being identified in 2012.

The LHC first powered up in 2008, but the construction work didn't stop there. The collider gets switched off for a while each year so that essential repairs and upgrades can take place. In 2017, one of the LHC's detectors, the Compact Muon Solenoid, or CMS, underwent a complex upgrade on its pixel detector, which will allow it to capture particle collisions in even finer detail.



Scientists conducting a 'heart transplant' to replace the pixel detector at the core of the CMS detector in March 2017

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The Compact Muon Solenoid (CMS) is just one of the giant detectors used at the LHC

30 petabytes

The amount of data stored from LHC experiments annually, enough to fill 1.2 million Blu-ray discs.

11,000

The number of circuits of the LHC each particle completes per second.

-271.3°C

The temperature at which the electromagnets of the LHC operate.

111

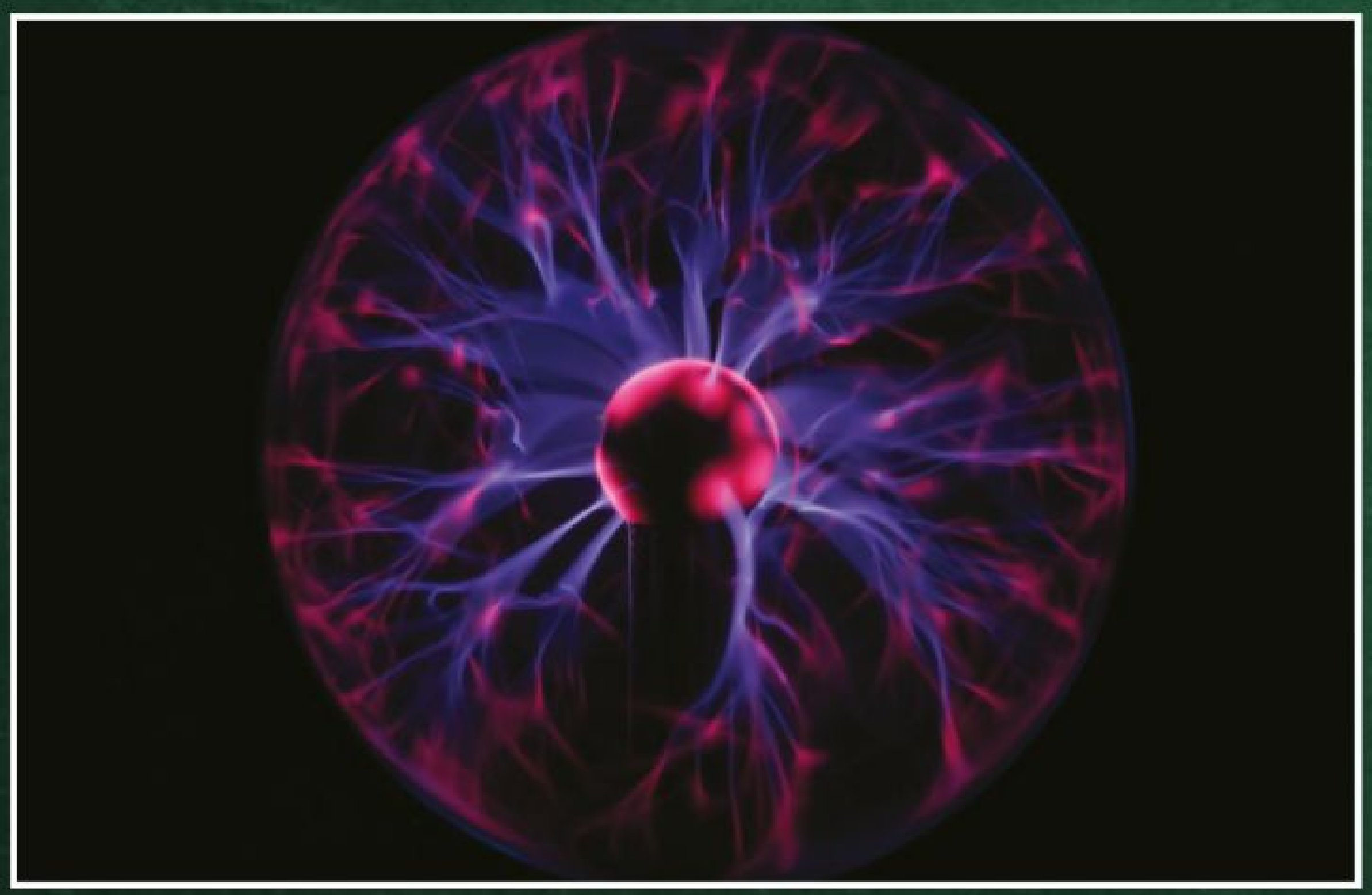
The number of nations involved in designing, building and testing the LHC.

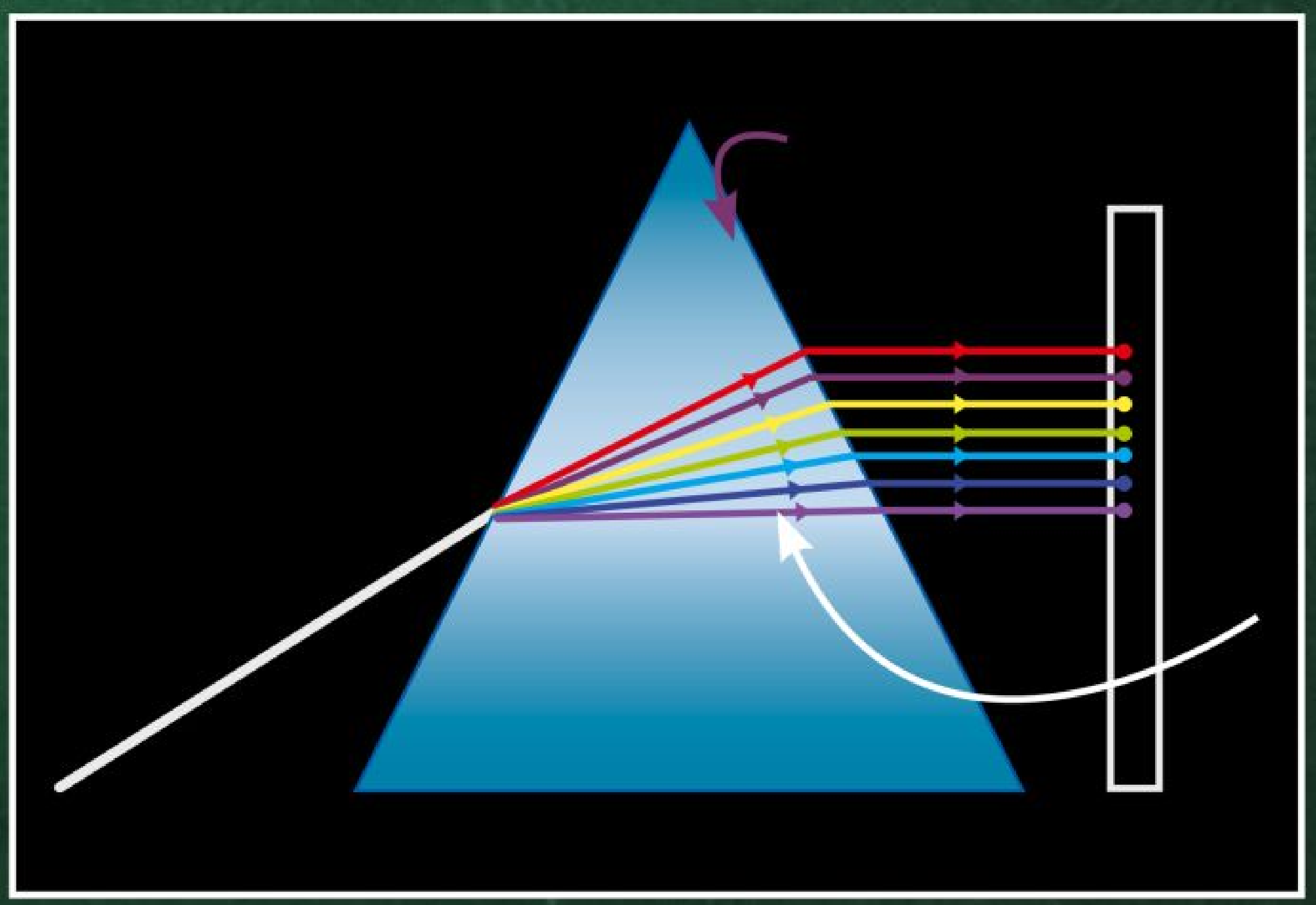
20 years

Projected lifetime of the LHC.

60 SECOND SCIENCE

DISCOVER THE FUNDAMENTAL PRINCIPLES IN PHYSICS THAT HAVE PAVED THE WAY FOR US TO UNDERSTAND OUR UNIVERSE





60 SECOND SCIENCE

Electricity explained

THE SHOCKING SCIENCE OF CIRCUITS, CURRENTS AND VOLTS

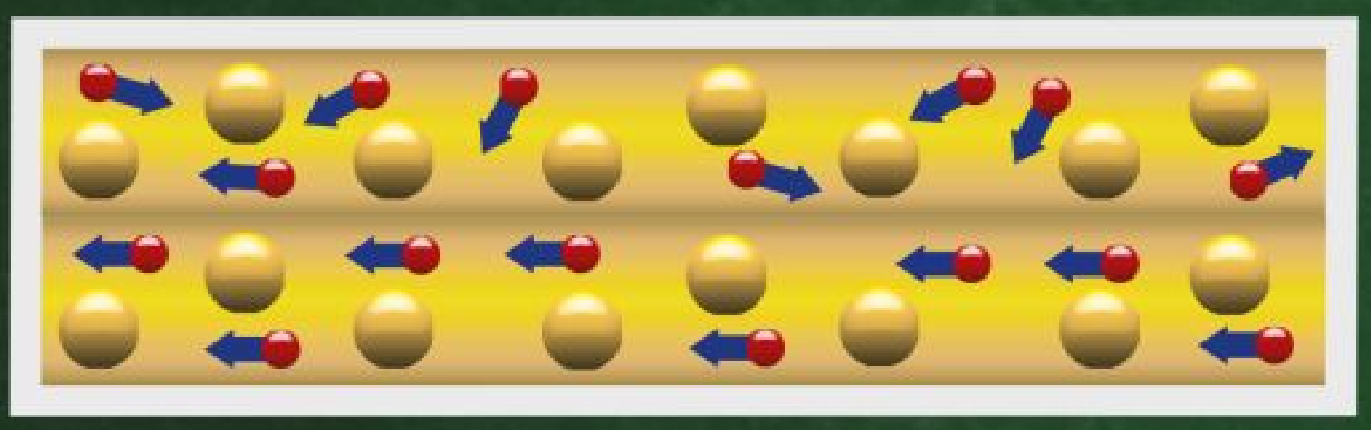
BACKGROUND

Electricity is a form of energy, and in combination with magnetism, it makes up one of the four fundamental forces of the physical world. It is generated by the movement of electrons, which are subatomic particles that orbit the nuclei of every atom.

In many materials, such as wood and plastic, electrons are held tightly alongside their atoms, but in some materials, such as metal, they can break free and move around on their own. Electrons have a negative charge, and it is the movement of this charge that creates electricity.

IN BRIEF

For electrons to move around and create a current, there has to be a circuit. This is a closed loop that allows a steady flow of electrons, carrying tiny amounts of electrical energy as they go. Circuits can be made from solid materials like copper wire, which have free electrons to carry the charge, and they can also be made from fluids containing charged ions, such as the salty fluid in our bodies, or from gases, such as air during a lightning strike. A circuit on its own isn't enough to produce an electric current; a voltage, or potential difference, is needed to get things moving. This can be provided by a battery, a generator, or by the build-up of static.

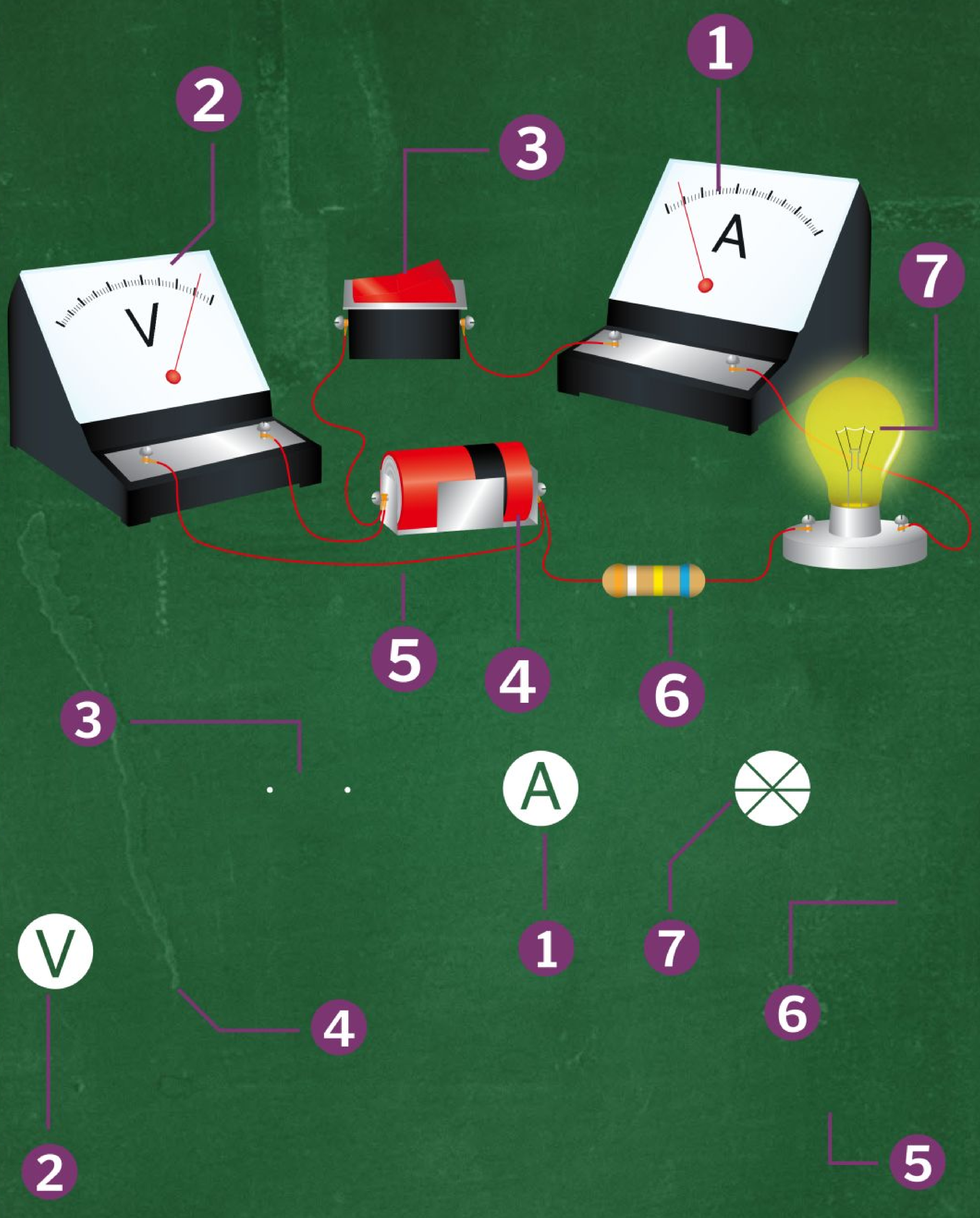


SUMMARY

Electricity is produced by the movement of charged particles – electrons or ions. It requires a complete circuit to flow, and it needs a potential difference to get the electrons moving.

Circuits uncovered

Discover the key components in a simple electrical circuit



1. Ammeter (in series)
Current is measured in amps. An ammeter can tell you the size of the current flowing through part of a circuit.

2. Voltmeter (in parallel)
Potential difference is needed to make a current flow, and it is measured in volts. Voltmeters can tell you the size of the potential difference across part of a circuit.

3. Switch
Circuits must be joined into a closed loop before current can flow. An open switch breaks the circuit.

4. Cell (or battery)
Batteries produce the potential difference that drives electrons around the circuit.

5. Wires
Wires connect up the components, providing a path for electrons moving around the circuit.

6. Resistor
This component reduces the flow of electricity, and is used to lower the voltage in a circuit.

7. Lamp
A filament lamp heats up and starts to glow as current passes through.

THE STORY OF ELECTRICITY

SOME OF THE FIRST EXPERIMENTS WITH ELECTRICITY WERE PERFORMED BY THE ANCIENT GREEKS, WHO OBSERVED THAT IF YOU RUBBED AMBER AGAINST FUR, IT WOULD ATTRACT DUST AND OTHER SMALL PARTICLES. IN FACT, THE WORD ELECTRICITY COMES FROM THE GREEK WORD FOR AMBER – ELEKTRON.

IT WASN'T UNTIL THE EXPERIMENTS WERE REPEATED IN THE 17TH AND 18TH CENTURY THAT THE SCIENCE OF ELECTRICITY STARTED TO EMERGE. AT FIRST, IT WAS THOUGHT THAT ELECTRICITY WAS A FLUID, AND DUTCH SCIENTISTS BUILT 'LEYDEN JARS' TO CONTAIN IT. THE GLASS JARS HAD METAL INSIDE AND OUT, AND COULD STORE A STATIC CHARGE.

IN 1752, BENJAMIN FRANKLIN DESCRIBED AN EXPERIMENT TO DEMONSTRATE THAT LIGHTNING WAS ELECTRICITY: BY FLYING A KITE WITH A KEY ATTACHED TO ITS STRING DURING A THUNDERSTORM. IN THE 1800S, ALESSANDRO VOLTA DISCOVERED THAT ELECTRICAL POTENTIAL COULD CAUSE AN ELECTRICAL CHARGE TO FLOW. HE USED THIS KNOWLEDGE TO INVENT BATTERIES.

The Doppler effect

HOW SOUND AND LIGHT WAVES CHANGE AS THEY MOVE TOWARDS OR AWAY FROM US

BACKGROUND

In the early 1840s, Austrian physicist Christian Doppler was the first to describe how sound and light waves seem to change as the distance between the source and an observer is increasing or decreasing. The theory was tested in 1845 by Christoph Buys Ballot. In his experiment, he asked musicians to play a constant note while on a moving train cart. The note he heard from the platform changed as the train sped past.

IN BRIEF

We've all heard how a siren changes as an ambulance rushes past. The pitch of an approaching siren will increase, then decrease as the vehicle speeds away. This is known as the Doppler effect, and is caused by sound waves effectively bunching together or stretching out. The pitch you hear is determined by the sound's frequency, or the number of waves per second. The siren's frequency doesn't change, but as the ambulance travels towards you, the same number of waves are compressed into a decreasing distance. This increases the frequency of the sound waves you hear, so the pitch seems higher. As the ambulance travels away, the sound waves are spread across a growing distance, reducing the frequency you hear so that the pitch seems lower.

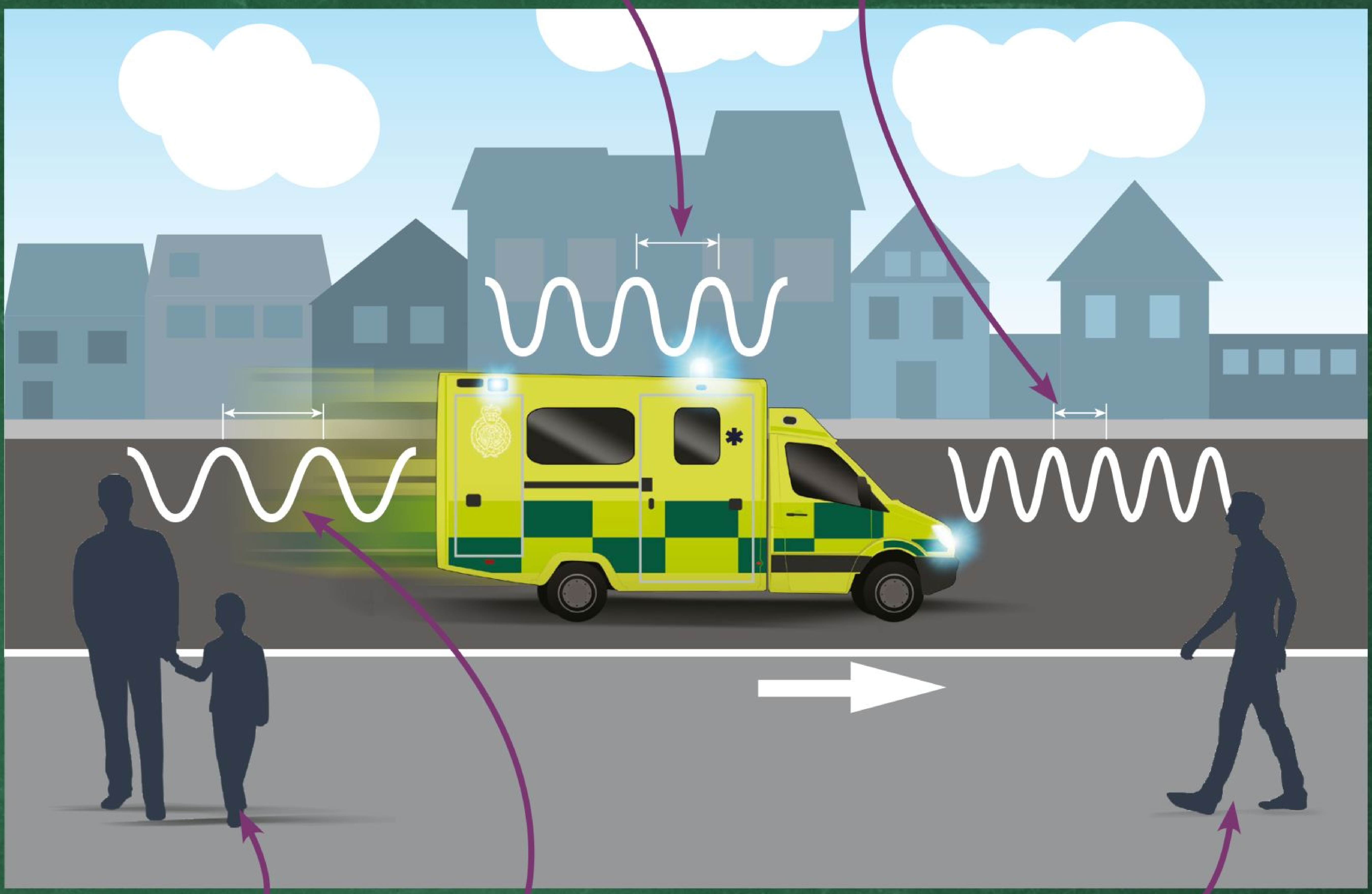
It's all relative: to people travelling in the emergency vehicle, the siren's pitch stays the same

SUMMARY

A sound's apparent pitch is relative to the changing distance between the noise source and the observer. Decreasing distances result in a higher pitch and increasing distances result in a lower pitch.

Doppler in action

Why the pitch of a siren seems to rise and fall



Siren
The siren actually blares at a constant frequency. To the ambulance driver, the pitch of the siren remains the same.

Driving towards
As the ambulance travels towards the observer, the waves are compressed into a smaller distance.

Observer 1
The apparent increase in wavelength and decrease in frequency is heard as a lower pitched siren.

Driving away
As the ambulance travels away, the same number of waves are spread over a larger distance.

Observer 2
To this observer, the siren's frequency appears to increase and its wavelength decrease, giving the impression of a higher pitch.

REDSHIFT AND BLUESHIFT

THE PRINCIPLE OF THE DOPPLER EFFECT APPLIES TO LIGHT AS WELL AS SOUND. THE FREQUENCY OF A LIGHT WAVE INDICATES ITS COLOUR, SO BY STUDYING HOW THE LIGHT OF A MOVING OBJECT CHANGES, IT IS POSSIBLE TO DETERMINE WHETHER IT IS MOVING TOWARDS OR AWAY FROM US. THIS IS THE METHOD THAT AMERICAN ASTRONOMER EDWIN HUBBLE USED TO CONCLUDE THAT MOST GALAXIES ARE MOVING AWAY FROM OUR OWN, THEREFORE THE UNIVERSE MUST BE EXPANDING. THE LIGHT FROM MOST COSMIC OBJECTS IS SHIFTED TOWARDS THE LOWER-FREQUENCY, RED END OF THE VISIBLE LIGHT SPECTRUM. THE LIGHT FROM SOME STARS AND GALAXIES IS SHIFTED TOWARDS THE BLUE END OF THE SPECTRUM, IMPLYING THEY ARE MOVING TOWARDS US.

Newton's Laws of Motion

THREE SIMPLE LAWS EXPLAIN THE EFFECT OF FORCES ON THE UNIVERSE AROUND US

BACKGROUND

Isaac Newton's famous Laws of Motion explain what happens to objects when forces are applied. A force is a push or a pull, like gravity, friction or magnetism. They can't be seen directly, but their effects can be measured; they can change the speed, shape or direction of movement of an object, and they are responsible for pressure and weight. Newton's three laws describe what happens when forces are balanced or unbalanced, and explain the idea of equal and opposite forces.

IN BRIEF

Newton's First Law explains what happens if the forces acting on an object are balanced. If an object is not moving, it won't start moving. And, if an object is already moving, it won't stop. This tendency is known as inertia.

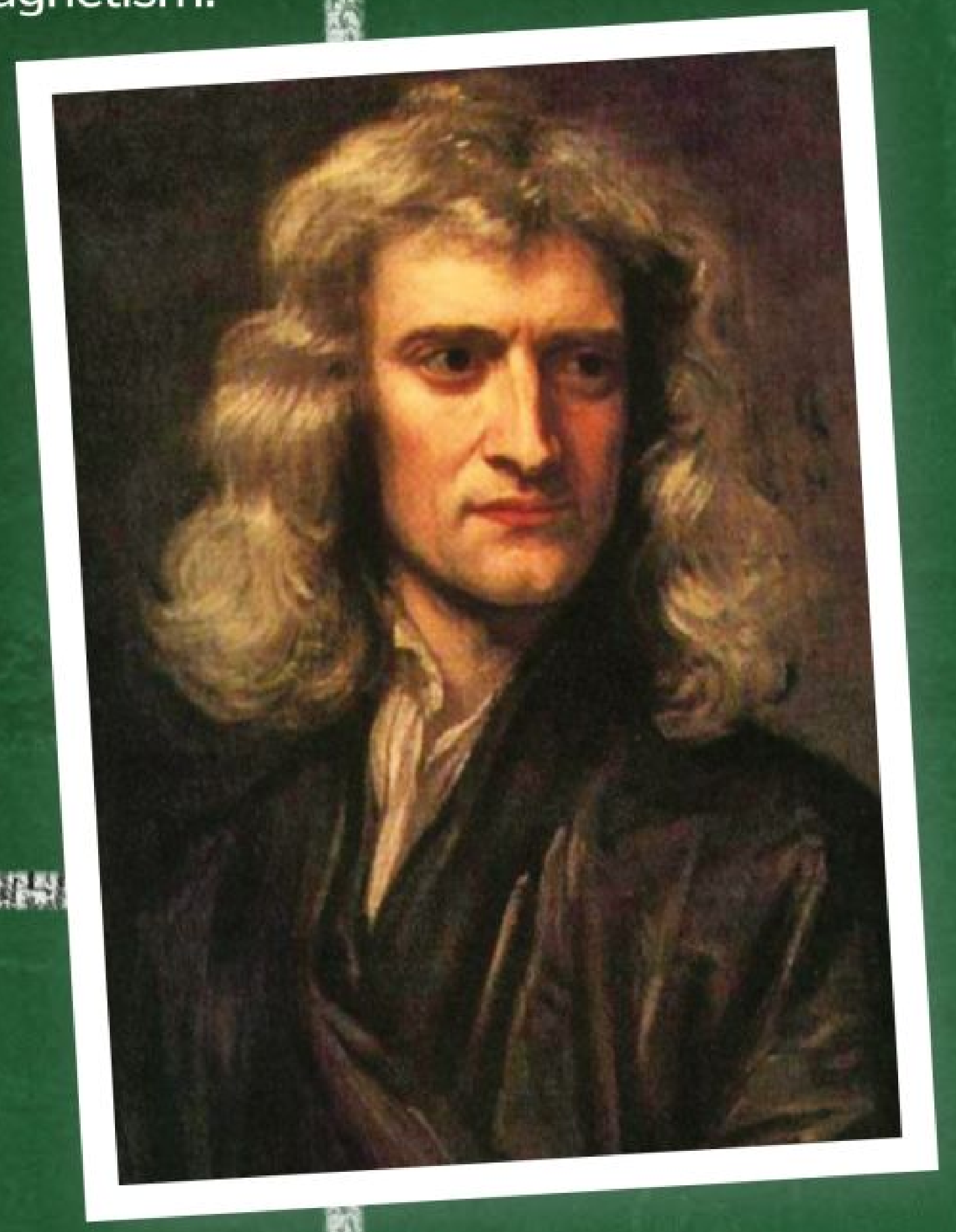
Newton's Second Law describes what happens if the forces acting on an object are unbalanced. If more force is applied in one direction, the object will accelerate. The more unbalanced the forces, the faster the object will accelerate. The more massive the object, the more force that is needed to make it move.

Newton's Third Law explains that for every action there is an equal and opposite reaction. Forces come in pairs; if one object exerts a force on another, the first object will exert an equal force in return. A simple example is the recoil of a gun; as the bullet flies forwards, the gun kicks back.

Newton's laws first appeared in his masterpiece, *Principia*, in 1687, and he developed them to explain why the orbits of the planets are ellipses, not circles.

SUMMARY

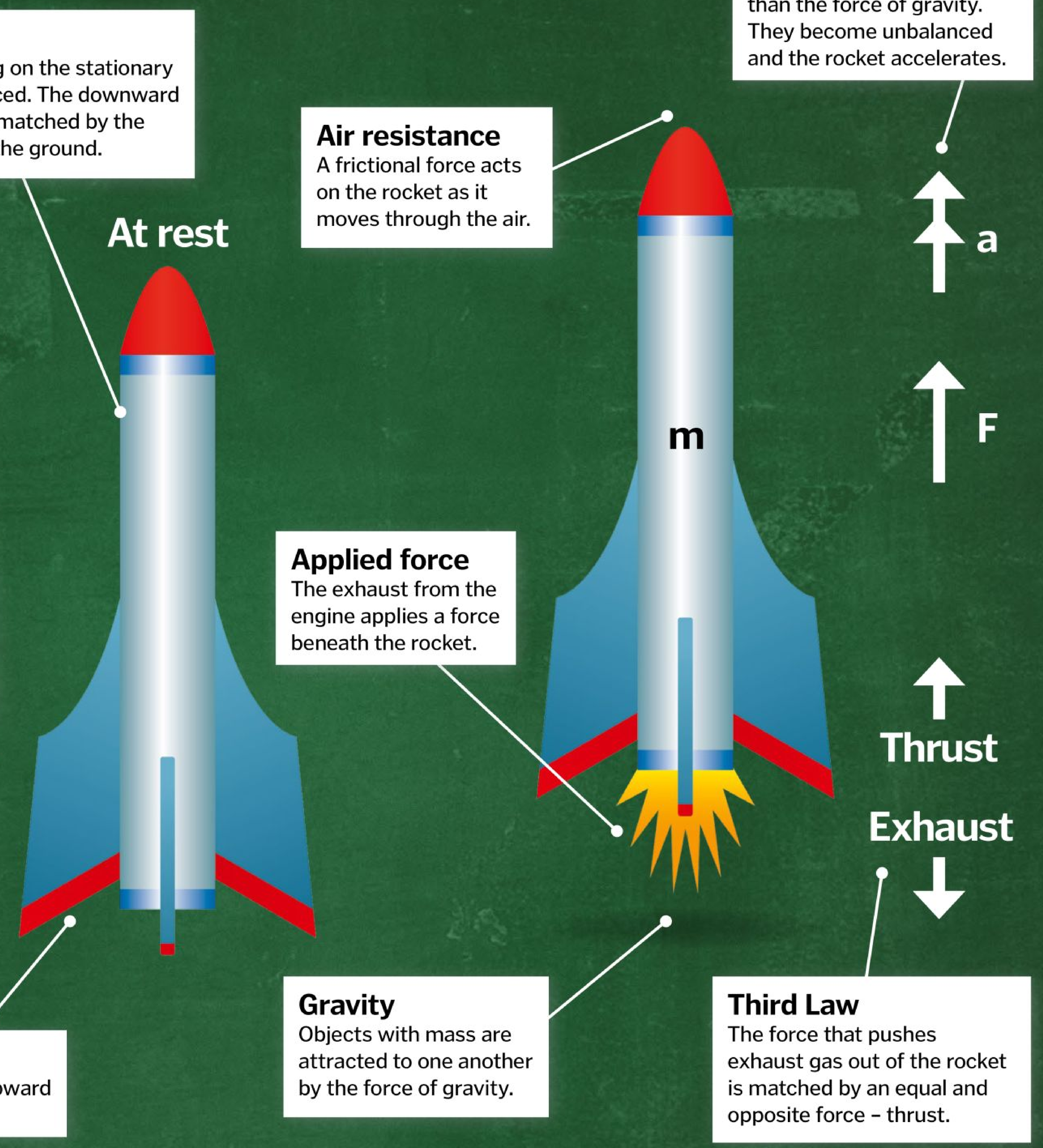
Newton's First Law describes what happens when forces are balanced. His Second Law describes what happens when they are unbalanced. The Third Law explains forces acting in equal and opposite pairs.



A portrait of a 46-year-old Isaac Newton, painted in 1689

Newton's Laws in action

The Laws of Motion govern the movement of everything around us



First Law
The forces acting on the stationary rocket are balanced. The downward pull of gravity is matched by the upward push of the ground.

Second Law
As the engines fire, the force of the thrust is greater than the force of gravity. They become unbalanced and the rocket accelerates.

Air resistance
A frictional force acts on the rocket as it moves through the air.

Applied force
The exhaust from the engine applies a force beneath the rocket.

Normal force
The Earth exerts an upward force on the rocket.

Gravity
Objects with mass are attracted to one another by the force of gravity.

Third Law
The force that pushes exhaust gas out of the rocket is matched by an equal and opposite force – thrust.

THE MAN BEHIND THE LAWS

SIR ISAAC NEWTON WAS A MATHEMATICIAN, PHYSICIST AND ASTRONOMER, BORN ON CHRISTMAS DAY IN 1642 (ACCORDING TO THE OLD JULIAN CALENDAR). HE DESCRIBED THE MECHANICS OF THE UNIVERSE WITH MATHS AND EQUATIONS IN HIS BOOK, THE *PHILOSOPHIAE NATURALIS PRINCIPIA MATHEMATICA* (COMMONLY KNOWN AS *PRINCIPIA*). HE EXPLAINED THE CONCEPT OF GRAVITY, AND SHOWED THAT EVERYTHING IN THE UNIVERSE IS GOVERNED BY THE SAME PHYSICAL LAWS. HE ALSO WORKED ON COLOUR THEORY, OPTICS AND CALCULUS, AND HIS IDEAS ARE STILL IN USE OVER 300 YEARS LATER.

HE WAS ONE OF THE GREATEST SCIENTISTS EVER TO HAVE LIVED, BUT HIS ACHIEVEMENTS DIDN'T STOP THERE. HE BUILT THE FIRST PRACTICAL REFLECTING TELESCOPE AND WAS ELECTED AS A MEMBER OF PARLIAMENT. HE EVEN BECAME MASTER OF THE ROYAL MINT, IN CHARGE OF THE PRODUCTION OF ALL OF BRITAIN'S CURRENCY FROM 1699 UNTIL HIS DEATH IN 1727.

60 SECOND SCIENCE

The general theory of relativity

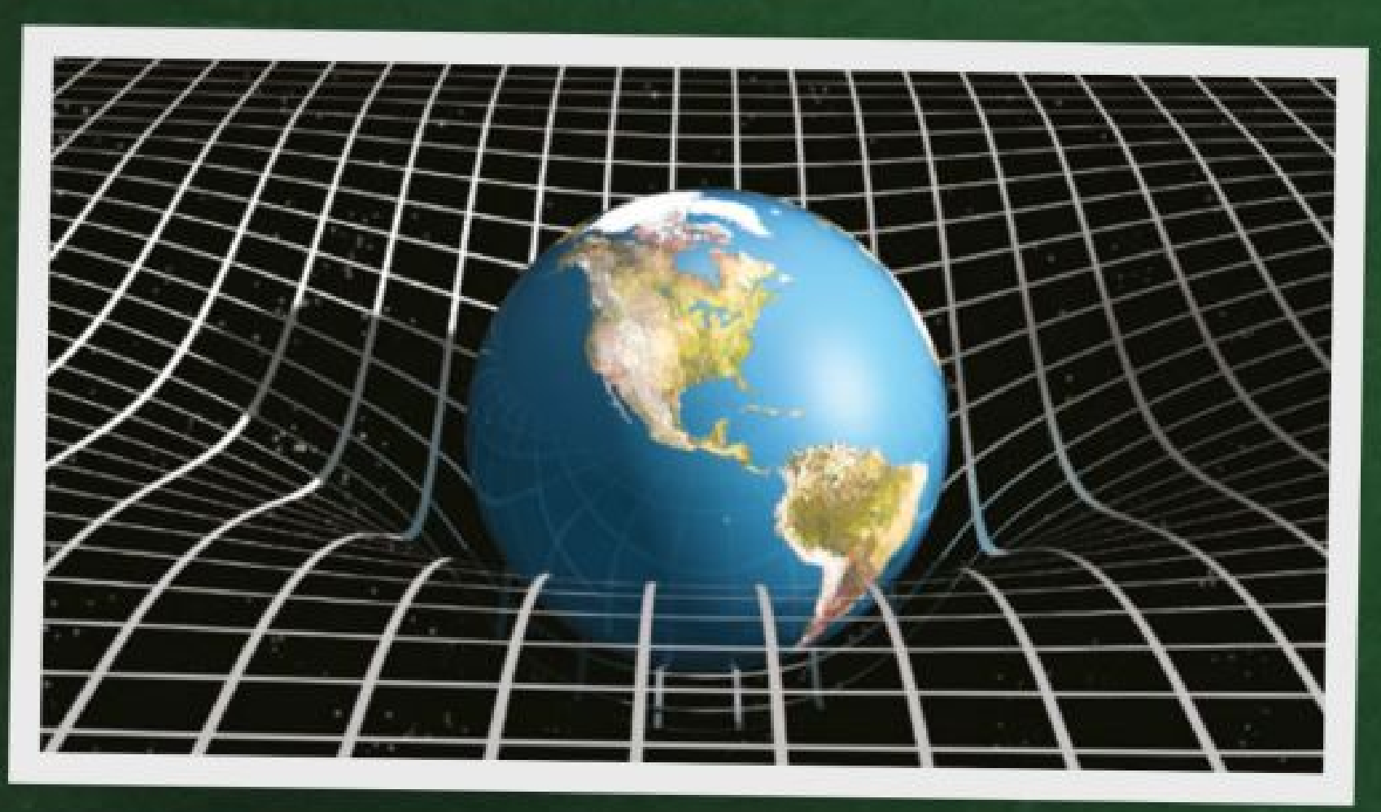
GET TO GRIPS WITH EINSTEIN'S THEORY OF THE UNIVERSE

BACKGROUND

In 1905, Albert Einstein published his theory of special relativity, explaining that the speed of light in a vacuum is constant and so are the laws of physics when they are observed while not accelerating. He proved that everything moves relative to everything else, but it only applied to special cases; it did not apply to observers who were speeding up or slowing down. Einstein set about extending his theory so that it could apply to everything in the universe, forming a theory of general relativity.

IN BRIEF

According to Isaac Newton's first law of motion, objects do not accelerate unless an external force acts upon them. However, Einstein realised that when you are in freefall, you feel weightless, so you feel no force even though you're accelerating towards the ground. He determined that what we experience as gravity must be the result of massive objects curving space-time itself. Any objects moving through this warped space-time follow as short a path as possible, which is a curve. This has helped to prove that Earth's orbit was not determined by gravity pulling it towards the Sun, as had been previously thought, but was rather the result of curved space-time forcing our planet along the shortest possible route around its host star.

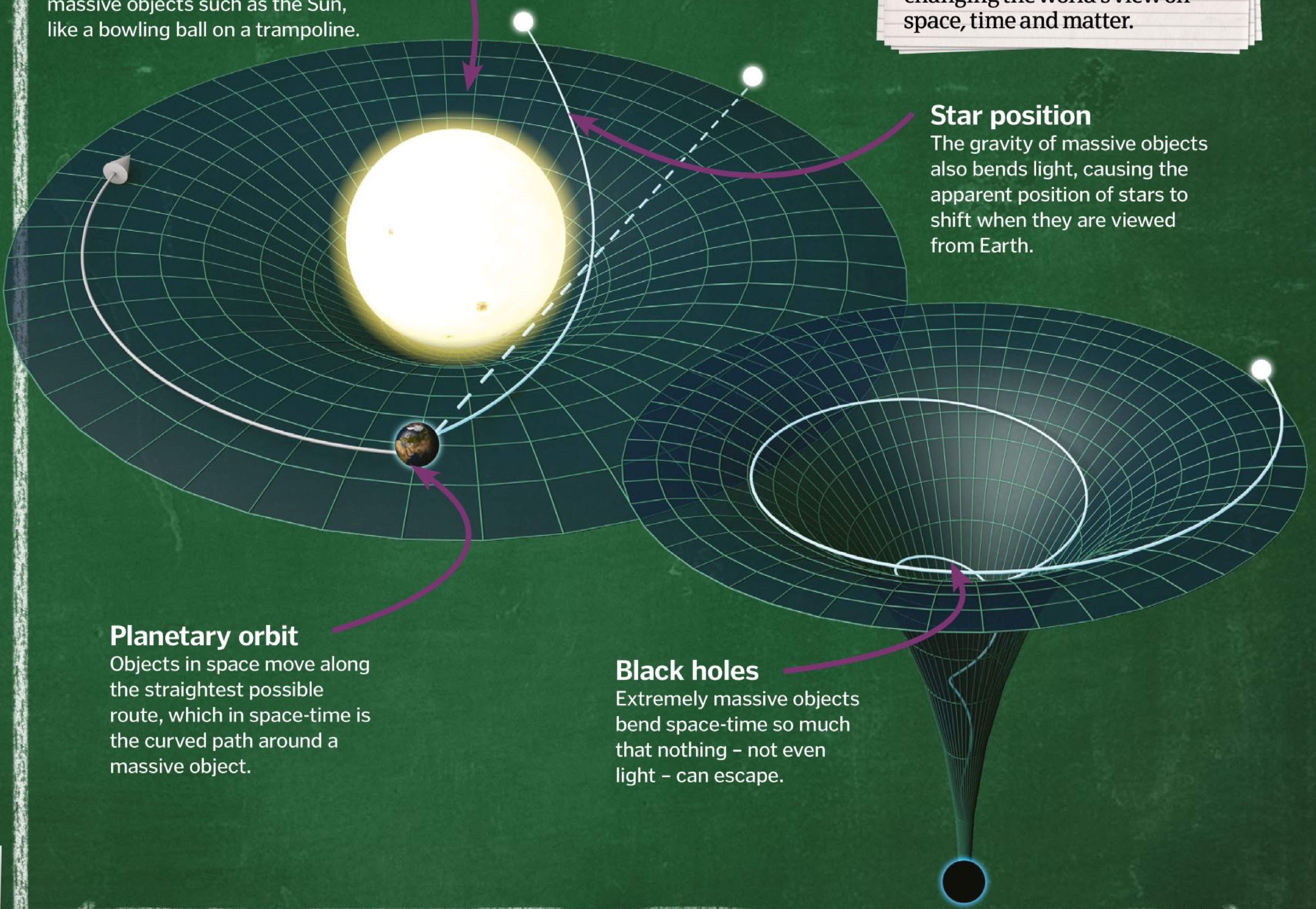


SUMMARY

The theory of general relativity proves that gravity is caused by the curvature of space-time and does not pull objects, but instead forces them along the shortest possible path.

Bending space-time

Explaining motion and the path of light in space



Curved space-time
Space-time can be visualised using the analogy of a flat sheet that bends under the influence of massive objects such as the Sun, like a bowling ball on a trampoline.

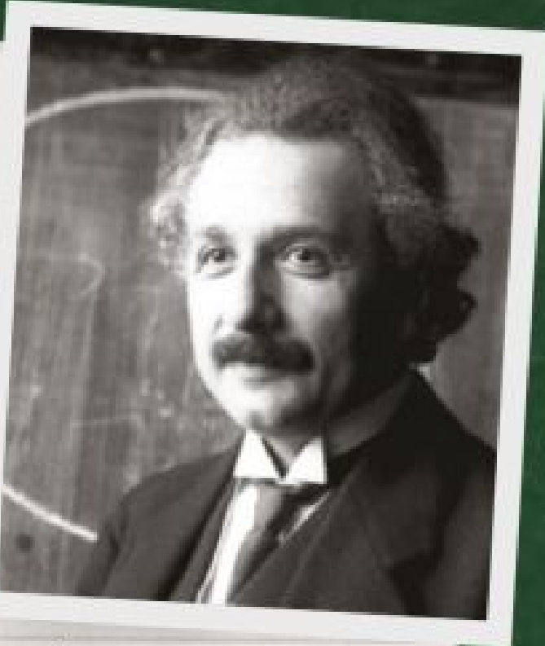
Star position
The gravity of massive objects also bends light, causing the apparent position of stars to shift when they are viewed from Earth.

Planetary orbit
Objects in space move along the straightest possible route, which in space-time is the curved path around a massive object.

Black holes
Extremely massive objects bend space-time so much that nothing – not even light – can escape.

Albert Einstein

1879-1955



Einstein considered his general theory to be the culmination of his life's research. After it was published in 1915, he became world famous almost overnight and in 1921, was awarded the Nobel Prize for Physics. He published more than 300 scientific papers in his lifetime, changing the world's view on space, time and matter.

HOW GENERAL RELATIVITY CHANGED THE WORLD

- EINSTEIN HAD SOLVED THE MYSTERY OF WHERE GRAVITY COMES FROM – THE CURVING OF SPACE-TIME.
- IT WAS DISCOVERED THAT THE CURVATURE OF SPACE-TIME AROUND EXTREMELY DENSE OBJECTS IS INFINITE, FORMING A HOLE IN THE FABRIC OF SPACE-TIME, KNOWN AS A BLACK HOLE.
- USING GENERAL RELATIVITY, EINSTEIN PROVED THAT GRAVITY BENDS THE PATH OF LIGHT AND GIVES STARS A FALSE POSITION IN THE SKY WHEN SEEN FROM EARTH.
- THE EQUATIONS OF GENERAL RELATIVITY HELPED REVEAL THAT THE UNIVERSE IS EXPANDING, LEADING TO THE DEVELOPMENT OF THE BIG BANG THEORY.

Hydraulics

THE SCIENCE BEHIND USING LIQUID POWER TO DO HEAVY LIFTING

BACKGROUND

Hydraulics is the system of using liquids to produce power. Liquids can't easily be compressed, so pushing on them transmits pressure through them. The pressure is evenly transferred through the liquid, so a small push can be used to create a large force elsewhere. This can be used to move pistons, which in turn can be used to perform work, such as lifting with a crane or braking a car.

IN BRIEF

Gases can be squashed, pushing the molecules closer together to fit into a smaller space, but liquids are hard to compress, as the molecules are close already. Particles bump around as they move, generating pressure. Push on a liquid, and pressure is increased.

In a container with two cylinders and two pistons, connected by a fluid, when you push down on a piston in the first cylinder, it will push a piston up in the second. The pressure is equal to the force applied, divided by the cross-sectional area of the piston.

Put a bigger piston at the other end of the container, and the pressure can be used to generate a larger force. You can see why if you rearrange the equation – force is equal to pressure multiplied by cross-sectional area. If the area of the second piston goes up, so does the force generated.

Hydraulics are used to perform heavy industrial work

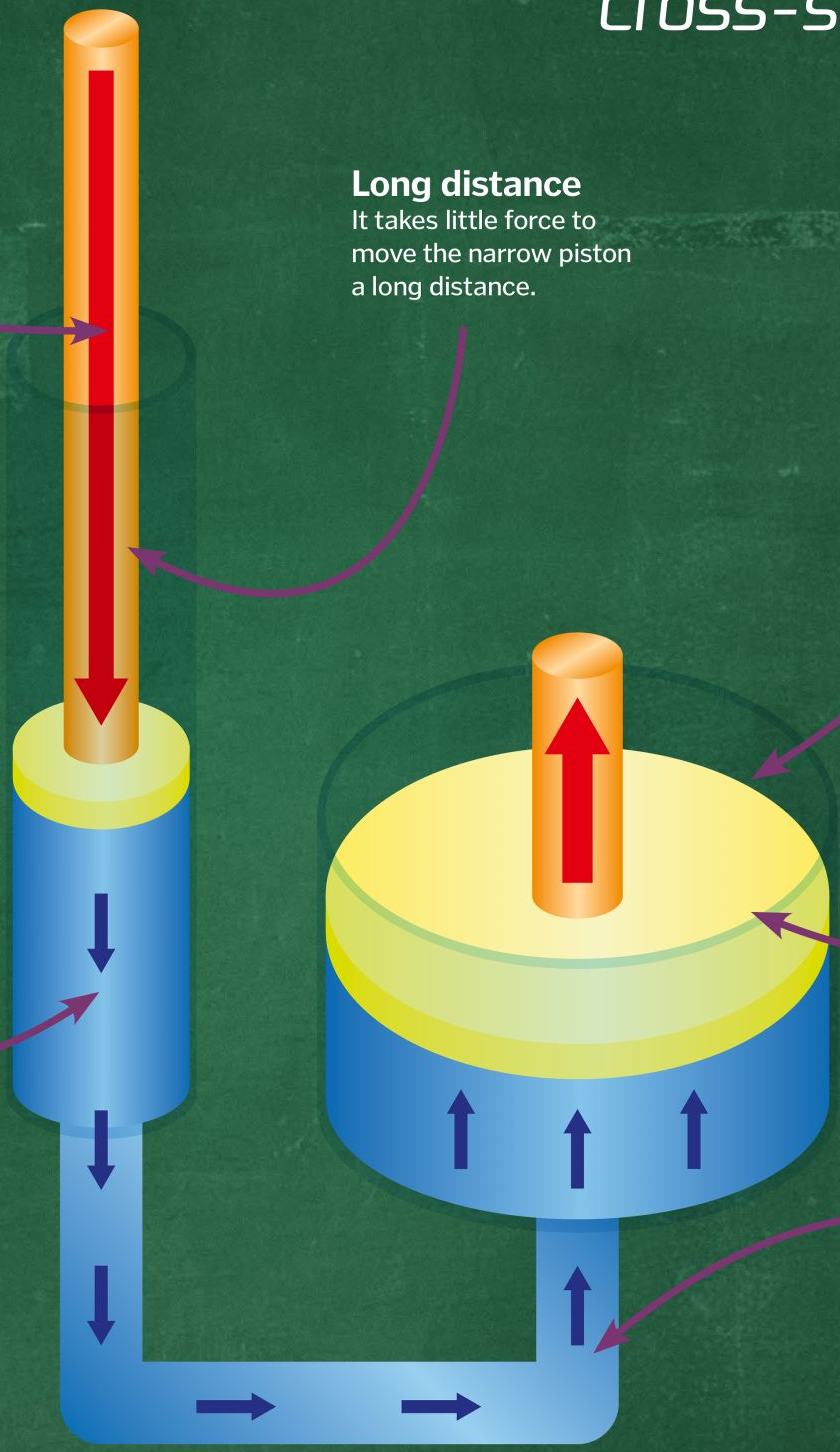
SUMMARY

Using a small piston to compress a fluid requires little force, but generates a lot of pressure. This pressure can be used to move a larger piston with even greater force.

Inside hydraulics

How do hydraulic systems generate so much force?

Force = pressure x cross-sectional area



Master piston
The narrow piston is pushed a long distance into the fluid.

Long distance
It takes little force to move the narrow piston a long distance.

Slave piston
The wide piston is pushed up a short distance by the fluid.

Short distance
The wide piston only moves a short distance, but applies much more force than the narrow one.

Incompressible fluid
The fluid inside the system is hard to compress. Pushing on it increases the pressure.

Even pressure
The pressure spreads evenly throughout the fluid, transmitting from one piston to the other.

PASCAL`S PRINCIPLE

BLAISE PASCAL WAS A FRENCH MATHEMATICIAN IN THE 17TH CENTURY, AND RESPONSIBLE FOR OUR UNDERSTANDING OF PRESSURE AND HYDRAULICS. HE EXPLAINED THAT WHEN YOU PUSH ON FLUID IN A CLOSED CONTAINER, THE PRESSURE IS TRANSMITTED EQUALLY IN ALL DIRECTIONS. A PRESSURE CHANGE AT ONE SIDE OF THE CONTAINER IS TRANSMITTED TO ALL OTHER PARTS OF THE CONTAINER, AND TO THE WALLS. THIS IS KNOWN AS PASCAL'S PRINCIPLE. HIS WORK ALSO INCLUDED UNDERSTANDING ATMOSPHERIC PRESSURE. SO IMPORTANT WERE HIS DISCOVERIES THAT THE STANDARD UNIT FOR PRESSURE WAS NAMED THE PASCAL (PA).PASCAL WAS A POLYMATH, AND ALSO WORKED ON THE FOUNDING PRINCIPLES OF PROBABILITY WITH PIERRE DE FERMAT.

60 SECOND SCIENCE

Light

A GUIDE TO HOW LIGHT TRAVELS, AND WHY IT MOVES FASTER THAN ANYTHING ELSE

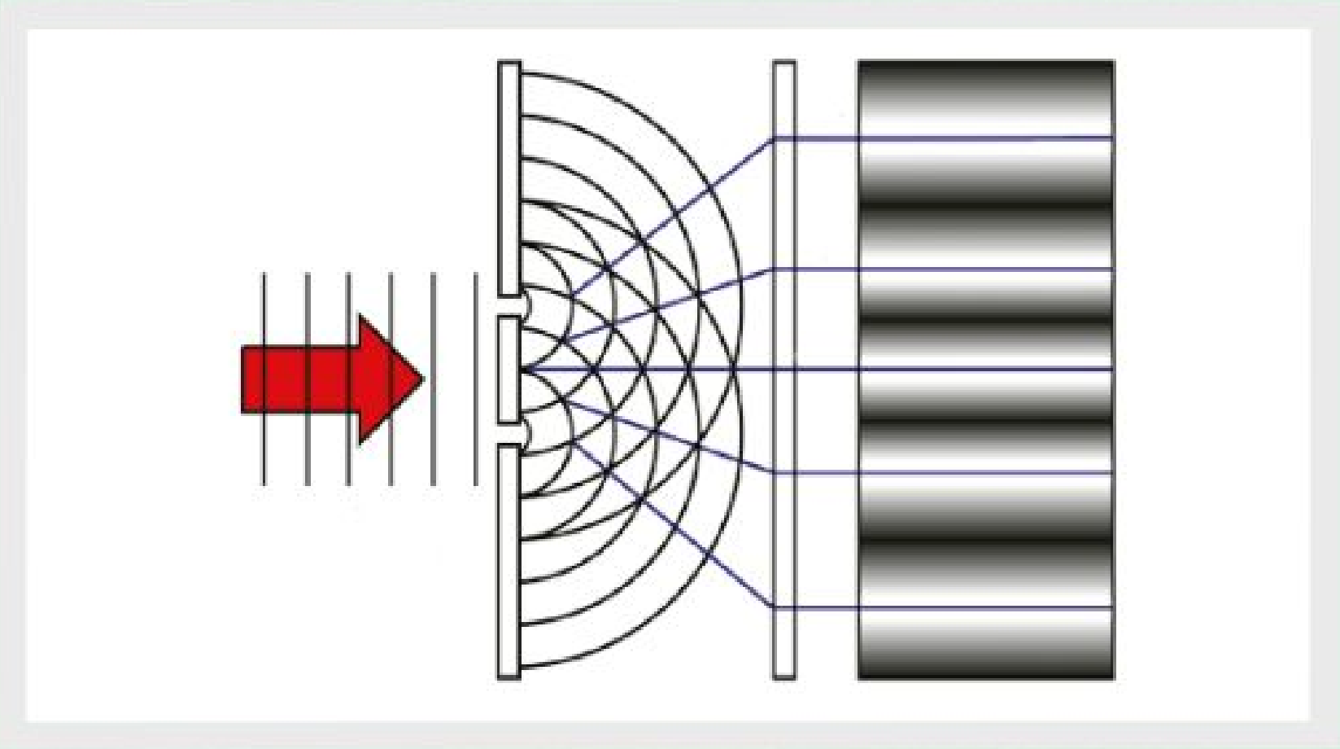
BACKGROUND

Light is electromagnetic radiation, and the word is mostly used to describe the parts of the spectrum we can see. It travels fast and in straight lines, but exactly how it does this is complicated. Isaac Newton favoured the particle theory, saying that light travelled in packages called 'corpuscles', while 17th century mathematician Christiaan Huygens proposed that light moved via waves, like sound. In fact, light is carried by particles called 'photons', which do travel and behave a bit like waves.

IN BRIEF

In 1801, physicist Thomas Young shone a beam of light through a pinhole, and allowed it to hit a piece of card with two slits. If light were carried by particles, it should have passed through the slits, lighting up two distinct spots. Instead, it formed bands, leading him to conclude that light is made up of waves. In 1860, James Clerk Maxwell extended this idea by explaining that light is actually electromagnetic waves, made up of electric and magnetic fields.

However, in the 1900s, Max Planck and Albert Einstein showed that electromagnetic radiation is divided into packets of energy called quanta, indicating that light is made up of particles, now known as photons.



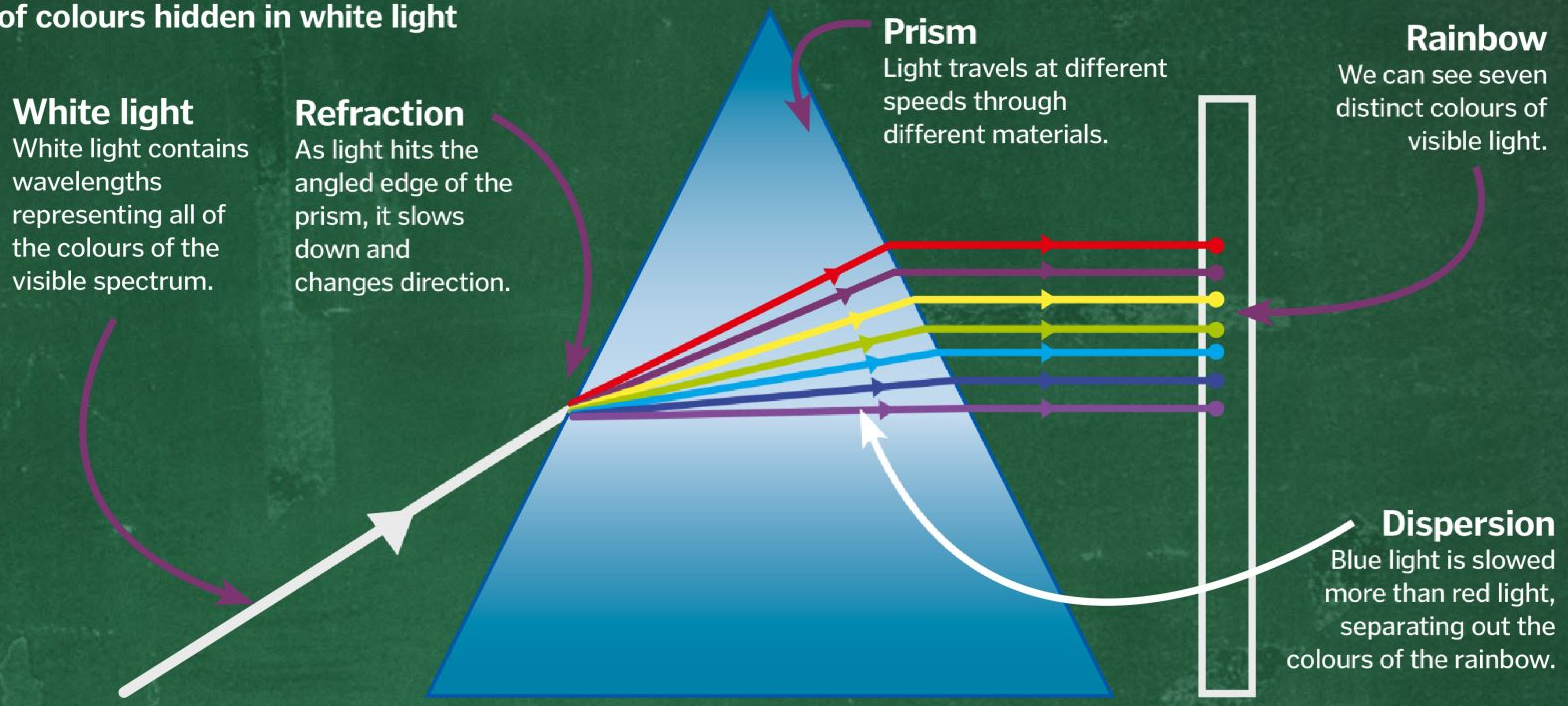
The two-slit experiment showed that light behaves like waves

SUMMARY

Physicists use both particle and wave metaphors to explain how light travels, and both ideas are valid. Photons behave like waves, and light can be described as both particles and as waves, or as neither.

Separating the spectrum

Prisms can be used to reveal the rainbow of colours hidden in white light



White light
White light contains wavelengths representing all of the colours of the visible spectrum.

Refraction
As light hits the angled edge of the prism, it slows down and changes direction.

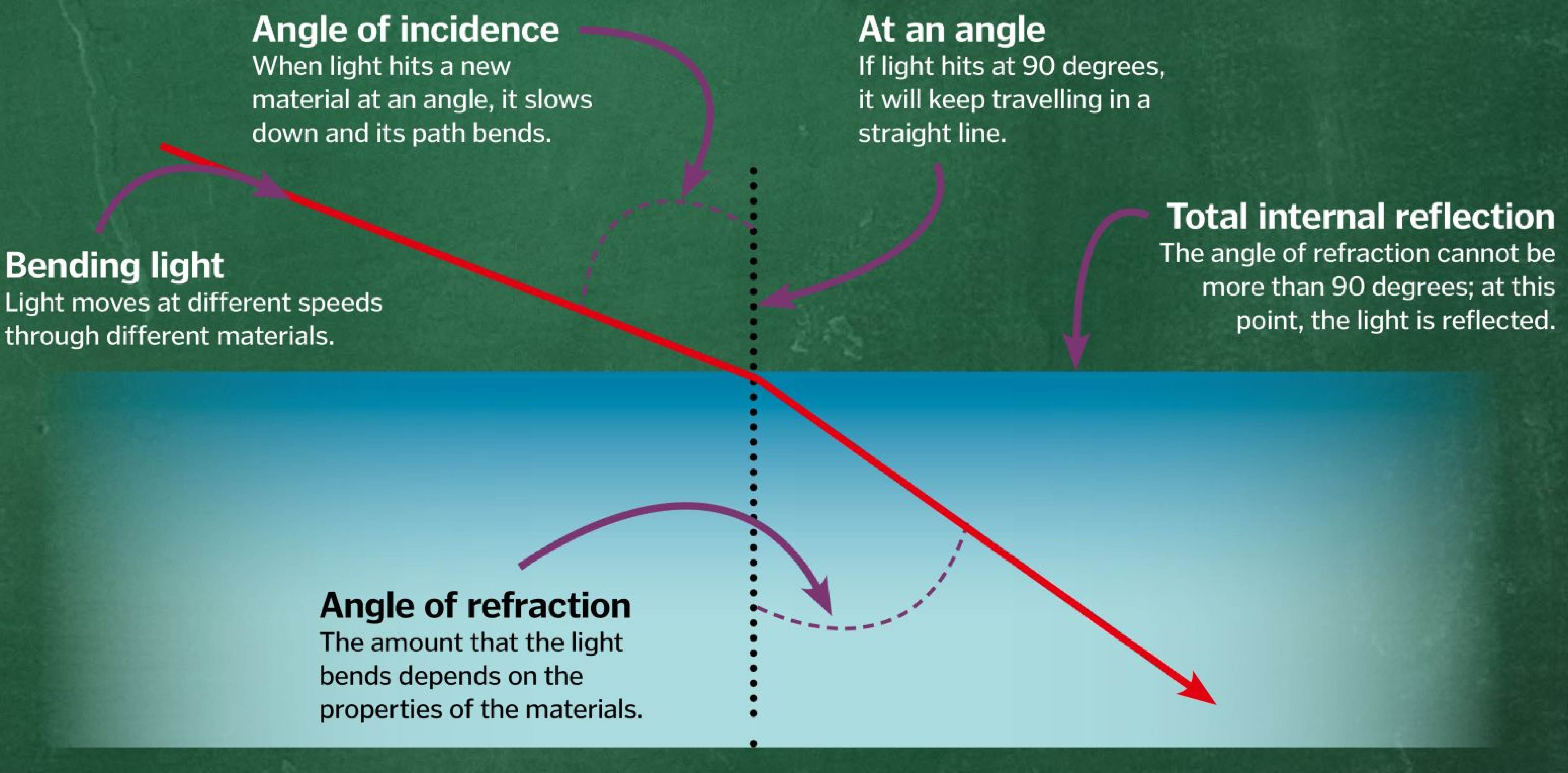
Prism
Light travels at different speeds through different materials.

Rainbow
We can see seven distinct colours of visible light.

Dispersion
Blue light is slowed more than red light, separating out the colours of the rainbow.

Bending light

As light travels from one material to another, its path can bend



Angle of incidence
When light hits a new material at an angle, it slows down and its path bends.

At an angle
If light hits at 90 degrees, it will keep travelling in a straight line.

Bending light
Light moves at different speeds through different materials.

Total internal reflection
The angle of refraction cannot be more than 90 degrees; at this point, the light is reflected.

Angle of refraction
The amount that the light bends depends on the properties of the materials.

THE SPEED OF LIGHT

THE SPEED OF LIGHT IN A VACUUM IS 300 MILLION METRES PER SECOND. BUT LIGHT DOESN'T ALWAYS MOVE THIS FAST. IN AIR, WATER AND OTHER MATERIALS, LIGHT INTERACTS WITH PARTICLES AND SCATTERS, SLOWING IT DOWN.

IN AIR, LIGHT IS ONLY SLOWED DOWN A LITTLE, BUT IN WATER, ITS SPEED DROPS TO AROUND 226 MILLION METRES PER SECOND, AND IN GLASS, DOWN TO 200 MILLION METRES PER SECOND. MOVING THROUGH DIAMOND, IT IS SLOWER, AT AROUND 150 MILLION METRES PER SECOND. RESEARCHERS AT HARVARD UNIVERSITY MANAGED TO SLOW IT DOWN TO 17 METRES PER SECOND BY SHINING IT THROUGH EXTREMELY COLD SODIUM ATOMS.

60 SECOND SCIENCE

Laws of thermodynamics

EXPLAINED! THE PHYSICS OF HOW ENERGY FLOWS

BACKGROUND

Energy is what makes everything happen, from getting out of bed to launching a rocket. For these things to occur, there needs to be an energy change – energy must be converted from one form to another. For example, chemical energy from your food is converted into kinetic energy when you move, along with thermal energy, or heat energy.

Thermodynamics is the branch of physics concerned with the relationship between heat and energy. Its four laws govern what happens in every energy change, and are key to understanding the world around us.

IN BRIEF

The first law of thermodynamics states that energy is always conserved, so the amount put into a system is the same as the amount that comes out. However, while the amount of energy remains the same, its usefulness decreases as it changes form. This is the second law of thermodynamics, and it's the reason why there's no such thing as a 100 per cent efficient machine. In other words, energy can't be recycled and some form of energy will need to be added in order to keep a machine running.

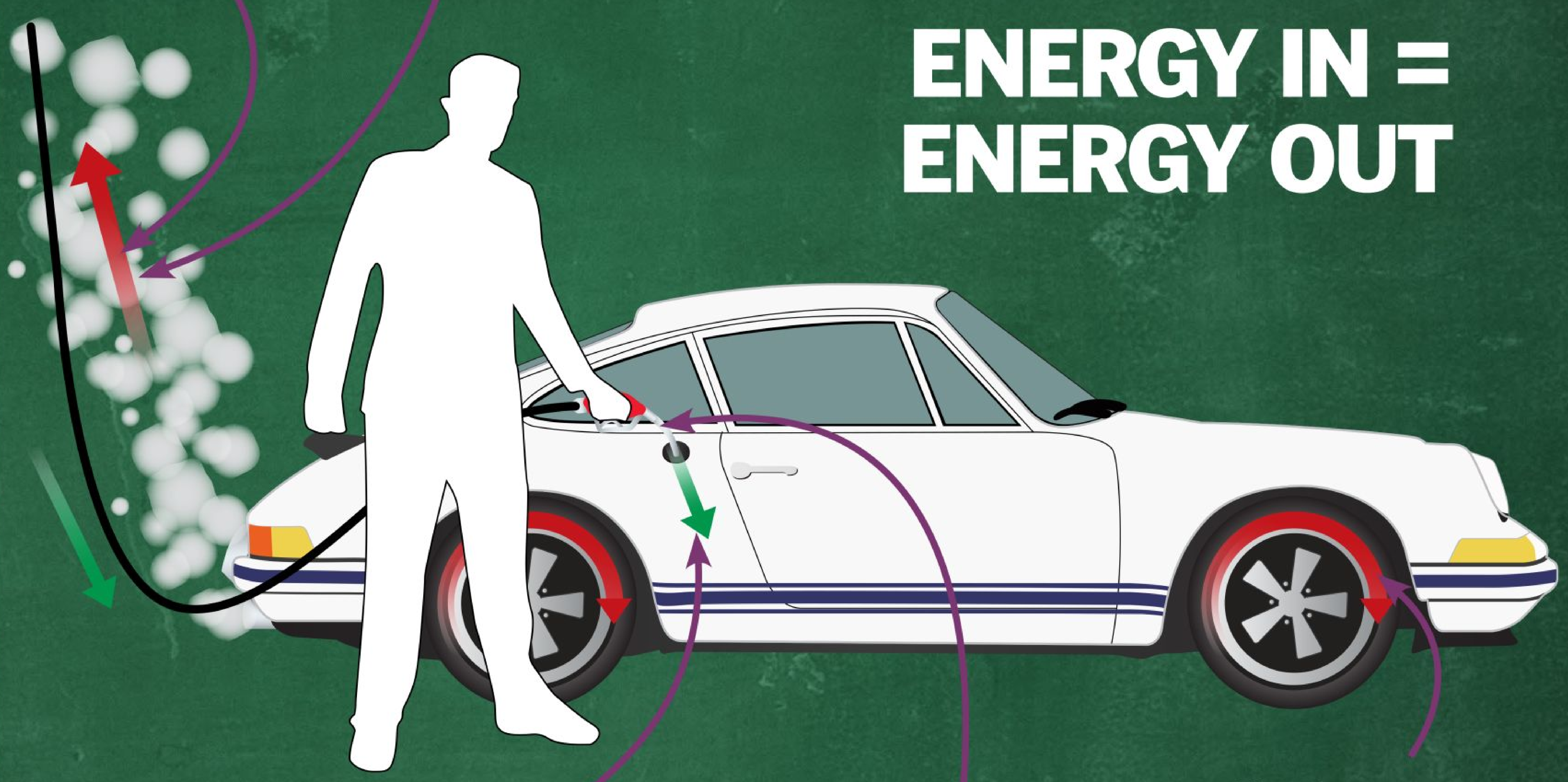
The 'zeroth' law defines the notion of temperature, while the third law states that a substance cannot reach absolute zero (-273.15 degrees Celsius), as its atoms would have no kinetic energy, which is impossible.

SUMMARY

The laws of thermodynamics explain the relationship between all types of energy. These principles are used to understand how all machines work, from human bodies to steam engines.

The first and second law

See the laws of thermodynamics in action in this simple example



Heat energy
Some of the fuel's energy is converted into heat energy, which spills out of the car's exhaust.

The second law
Although no energy has been lost, it has become less concentrated as it has spread out into the surroundings.

The first law
The amount of kinetic energy and heat energy created is equal to the amount of energy stored in the fuel.

ENERGY IN = ENERGY OUT

Concentrated energy
Fuels such as gasoline store highly concentrated potential energy in their chemical bonds.

Inefficient system
The less concentrated energy cannot be reused, so when the fuel runs out, the flow of energy stops.

Kinetic energy
In the car's engine, some of the fuel's energy is converted into kinetic energy, which spins the wheels.

THE FOUR LAWS

- ZEROTH LAW OF THERMODYNAMICS
IF TWO OBJECTS WITH THE SAME TEMPERATURE ARE TOUCHING, THERE IS NO NET FLOW OF ENERGY FROM ONE OBJECT TO THE OTHER.

- FIRST LAW OF THERMODYNAMICS
ENERGY CANNOT BE CREATED OR DESTROYED, IT CAN ONLY BE TRANSFORMED.

- SECOND LAW OF THERMODYNAMICS
AS ENERGY TRANSFORMS, IT BECOMES LESS CONCENTRATED AND THEREFORE LESS USEFUL.

- THIRD LAW OF THERMODYNAMICS
IT IS NOT POSSIBLE TO GET THE TEMPERATURE OF A SUBSTANCE DOWN TO ABSOLUTE ZERO (0 DEGREES KELVIN/-273.15°C).

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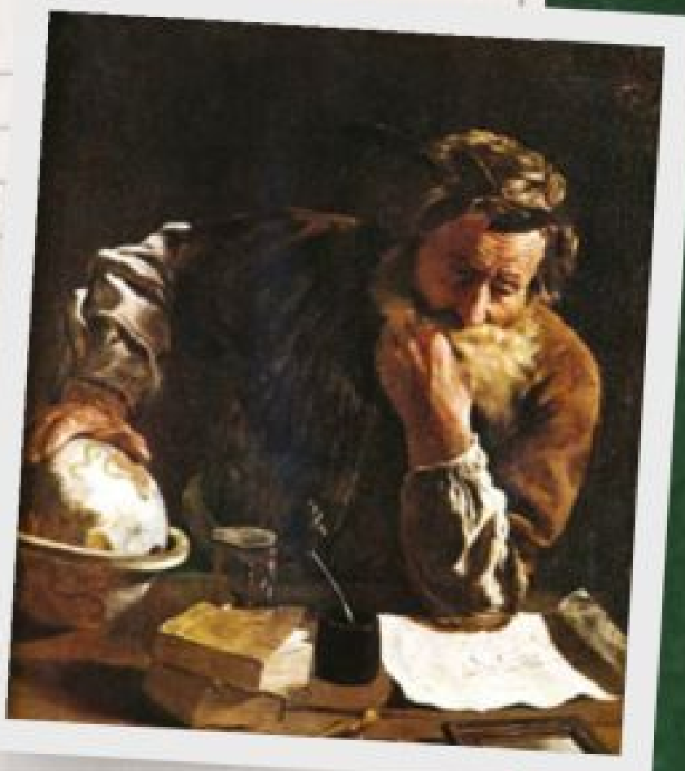
Archimedes’ principle

FIND OUT WHY BOATS FLOAT ON WATER

Archimedes

287 BCE – 212 BCE



Mathematician, astronomer, engineer and inventor, Archimedes was one of the most brilliant minds in ancient Greece. He was famous for his discoveries about buoyancy and density, his work on pulleys and levers, and his contributions to the field of geometry. It is even reported that he devised a system of mirrors that focused the Sun onto enemy ships to make them combust.

BACKGROUND

According to the Roman author Vitruvius, King Hiero II of Syracuse commissioned a goldsmith to make him a crown, but upon receiving it, was not convinced it was pure gold. He asked Archimedes to determine whether he had been ripped off.

Archimedes couldn’t melt the crown or damage it, and chemical analysis had not been invented. He had to find alternative means of determining its purity. The experiments that followed were the basis of our understanding of density and buoyancy.

IN BRIEF

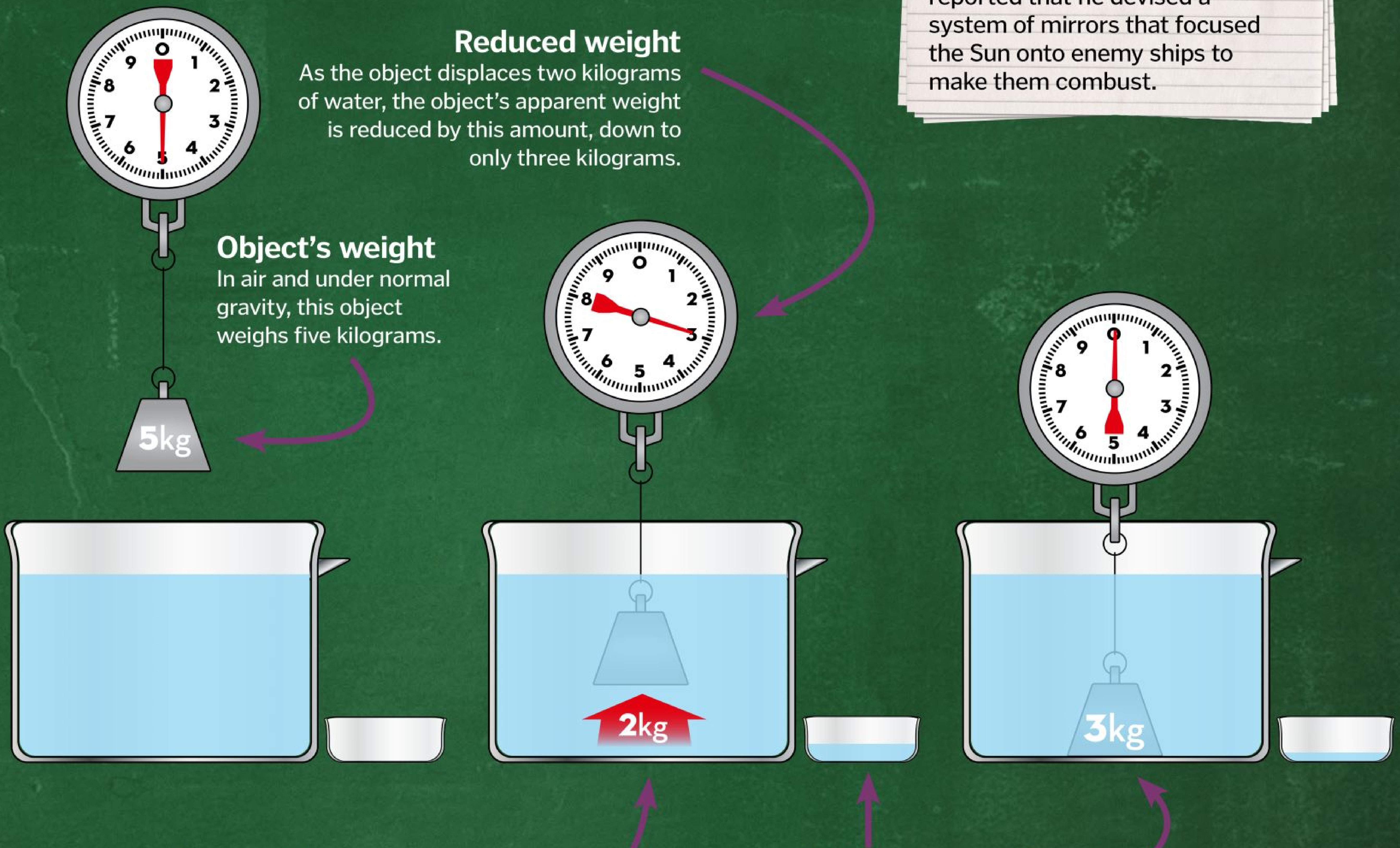
The ‘eureka’ moment reportedly came while Archimedes was taking a bath. When he climbed in, the water level rose and he realised that the volume of water he displaced must be equal to his body’s volume. If he was bigger, more water would spill onto the floor. He also noticed that the water must be pressing up against him to support his weight, otherwise he would sink to the bottom. This force is now called buoyancy, and is due to the fact that fluid pressure increases with depth. The buoyant force counteracts the object’s weight, pushing up with an equal force. But if the object is heavier than the volume of water it displaces (meaning it is denser than water), it will sink. Using this logic, Archimedes proved that the king’s crown was not pure.

SUMMARY

Fluids exert a buoyant force on objects completely or partially submerged in them, and the size of this force is equal to the weight of the fluid displaced by the object.

The theory in action

See how Archimedes’ principle works in this simple experiment



Reduced weight
As the object displaces two kilograms of water, the object’s apparent weight is reduced by this amount, down to only three kilograms.

Object’s weight
In air and under normal gravity, this object weighs five kilograms.

Buoyant force
Buoyancy counteracts gravity, pushing up with a force equal to the weight of the water that has been displaced.

Volume
The object’s volume is equal to the volume of water displaced, a fundamental part of Archimedes’ discovery.

Density
This object is denser than the water, so its weight is greater than the weight of the fluid it displaces. This means that it sinks to the bottom.

WHERE IS ARCHIMEDES’ PRINCIPLE USED TODAY?

- IT’S USED TO CALCULATE HOW DEEP A SHIP WILL SINK WHEN IT’S LOADED WITH CARGO, WHICH ALLOWS ENGINEERS TO FIGURE OUT A CONTAINER SHIP’S MAXIMUM LOAD.

- JUST AS ARCHIMEDES REPORTEDLY VERIFIED THE KING’S CROWN, THIS PRINCIPLE CAN STILL BE USED TO ASSESS THE PURITY OF EXPENSIVE ITEMS SUCH AS JEWELLERY.

- HYDROMETERS USE ARCHIMEDES’ PRINCIPLE TO MEASURE THE RELATIVE DENSITY OF SPECIFIC LIQUIDS, BY OBSERVING HOW DEEP AN OBJECT SINKS WITHIN THEM.

- BALLAST TANKS IN SUBMARINES USE THIS PRINCIPLE TO ALLOW THE SUB TO STAY AT ANY CHOSEN DEPTH, WITHOUT FLOATING TO THE SURFACE OR SINKING FURTHER.

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States of matter

THE CHEMISTRY OF SOLIDS, LIQUIDS, GASES AND PLASMA EXPLAINED

BACKGROUND

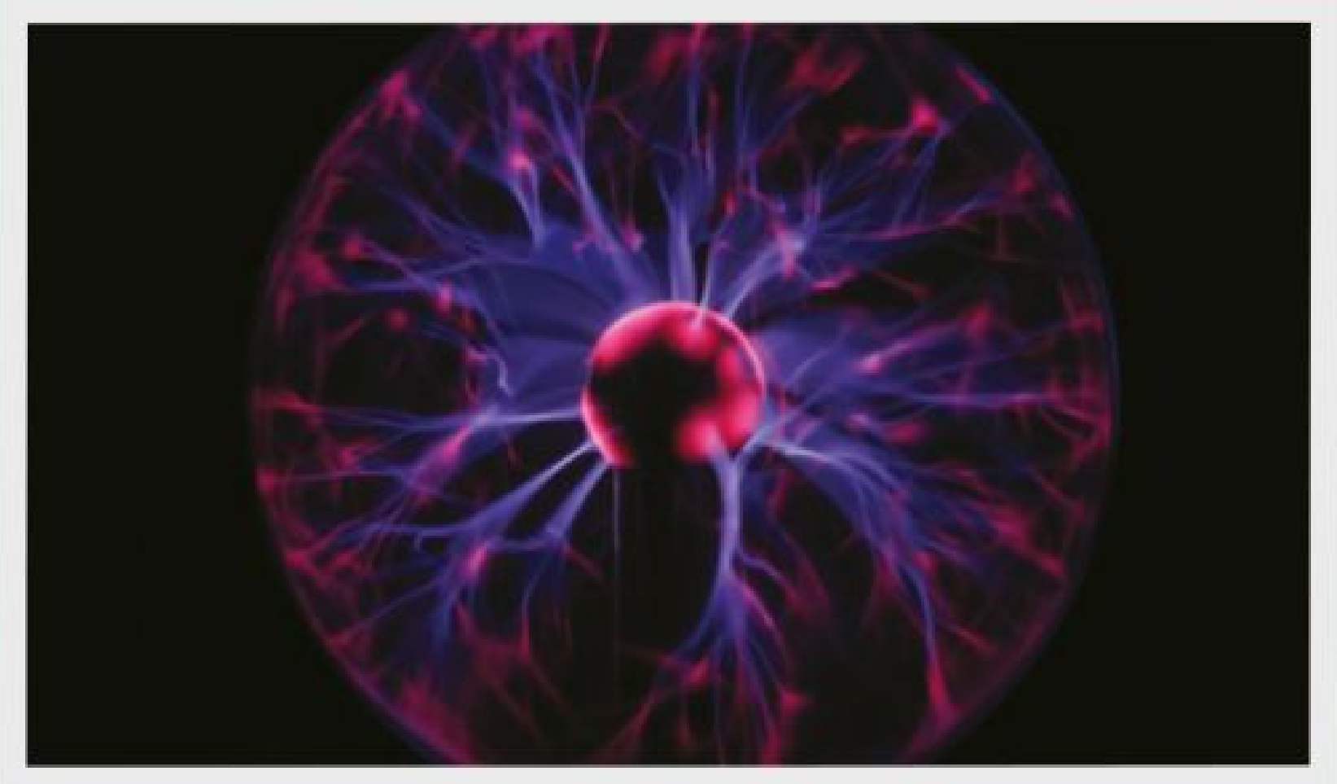
Matter can exist in different forms depending on the environment. There are four fundamental states: solid, liquid, gas and plasma. On Earth, we are most familiar with the first three, but the most common state in the universe is actually plasma.

There are several other states of matter that are rarer, including Bose-Einstein condensates, quark-gluon plasma, and degenerate matter.

IN BRIEF

The states of matter that we are all familiar with are solids, liquids and gases. The particles that make up solids are packed so tightly together that they barely move. They can be made up of mixtures of different atoms, or from repeating patterns of the same atoms that fit together to form crystals.

Liquids are looser. The particles are close together, but aren't in fixed positions. This means that they can flow. Gases are more loosely packed. The particles are far apart, and they move around rapidly in different directions, expanding to fill a container. The fourth state of matter is plasma. It is a bit like gas, but the atoms themselves have broken apart, becoming ionised and forming a sea of free electrons and atomic nuclei.



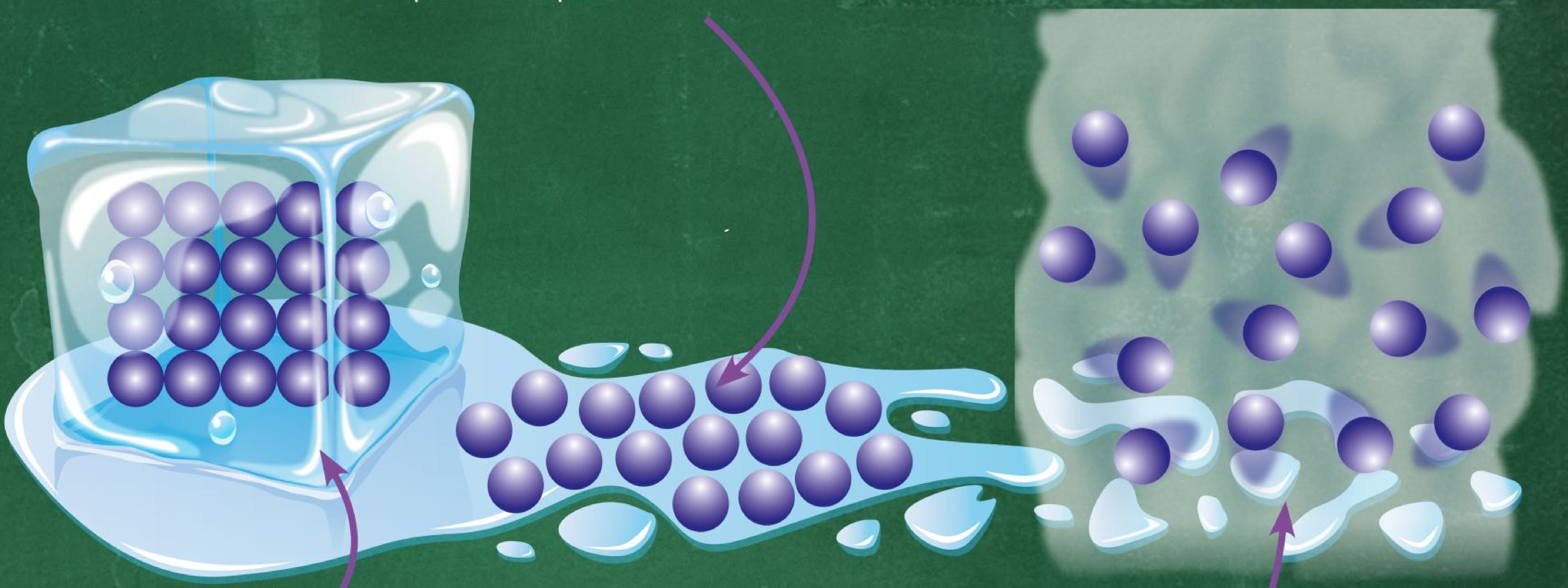
As electricity passes through gas, it breaks down to form filaments of glowing plasma

SUMMARY

The main states of matter are solids, liquids and gases. Their properties differ; particles in solids are static, in liquids they move much more freely, and in gases they move quickly in all different directions.

States of water

On Earth, water naturally exists in all three states



Water
Between 0 and 100 degrees Celsius, water is liquid. The molecules are still close together, but they move more freely. Clumps of molecules slide past one another, and groups form and break apart as the liquid flows.

Ice
Below 0 degrees Celsius, water is a solid. The molecules line up to form a neat crystal structure, and barely move from their original positions.

Steam
Above 100 degrees Celsius, water becomes a gas. Individual molecules are far apart and can't hang on to each other to form groups or solid structures. Instead, they move around on their own.

> *"As the temperature increases, the particles gain energy and are able to move past each other"*

FROM ONE STATE TO ANOTHER

IN NATURE, MATTER CAN TRANSITION BETWEEN THE FUNDAMENTAL STATES, TURNING FROM PLASMA, TO GAS, TO LIQUID, TO SOLID AND BACK AGAIN. AT COLD TEMPERATURES, PARTICLES HAVE LITTLE KINETIC ENERGY AND ARE FIXED IN POSITION, FORMING A SOLID. AS THE TEMPERATURE INCREASES, THE PARTICLES GAIN ENERGY AND ARE ABLE TO MOVE PAST EACH OTHER. AT THIS POINT THE MATTER IS IN A LIQUID STATE. WITH A FURTHER TEMPERATURE INCREASE, THE PARTICLES HAVE ENOUGH ENERGY TO MOVE FREELY, AND THE MATTER IS A GAS. UNLESS THEY ARE IN A CONTAINER, THE ATOMS WILL SPREAD OUT INFINITELY. IF THE ATOMS BECOME HOT ENOUGH, THEIR ELECTRONS ARE STRIPPED AND THEY EVENTUALLY BECOME PLASMA.

THE SCIENCE OF MUSIC

How do we make music, and what happens when it hits our ears?

Music is an ancient part of our culture, and has a powerful influence over our minds. Songs can make people laugh, cry, dance, or cover their ears in disgust, and everyone has their own favourites.

Sound is generated by vibrations. When the strings of an instrument vibrate, they push the air in front of them (compression) and the air behind them expands (rarefaction). These compressions and rarefactions create waves that move through the air.

When the sound waves reach your ears, they push on the air in your ear canals and set your ear drums moving. These vibrations then trigger the movement of three tiny bones, which send the vibrations on to a fluid-filled structure called the cochlea. The motion of the fluid in this coil is used to generate electrical signals that travel to the brain. But this is just a tiny part of the story.

These simple vibrations can cause a powerful emotional response, and there are layers of complexity in the notes themselves, and in the way that our brains perceive them.

The sound waves that reach your ears carry a huge amount of information. The basics of musical notes come down to volume, pitch and timbre (or tone); the bigger the vibrations are, the louder the sound is, and the more frequently the vibrations happen, the higher the pitch. And as for timbre, that is determined by the smoothness of the sound wave itself.

Standard waves drawn in physics textbooks are very smooth, but sounds produced by the human voice or by instruments aren't so even. It's the little imperfections that add up to produce the timbre, or tone, of the final notes. Then there is echo, reverberation, and resonance, and layer upon layer of instruments, voices and lyrics.

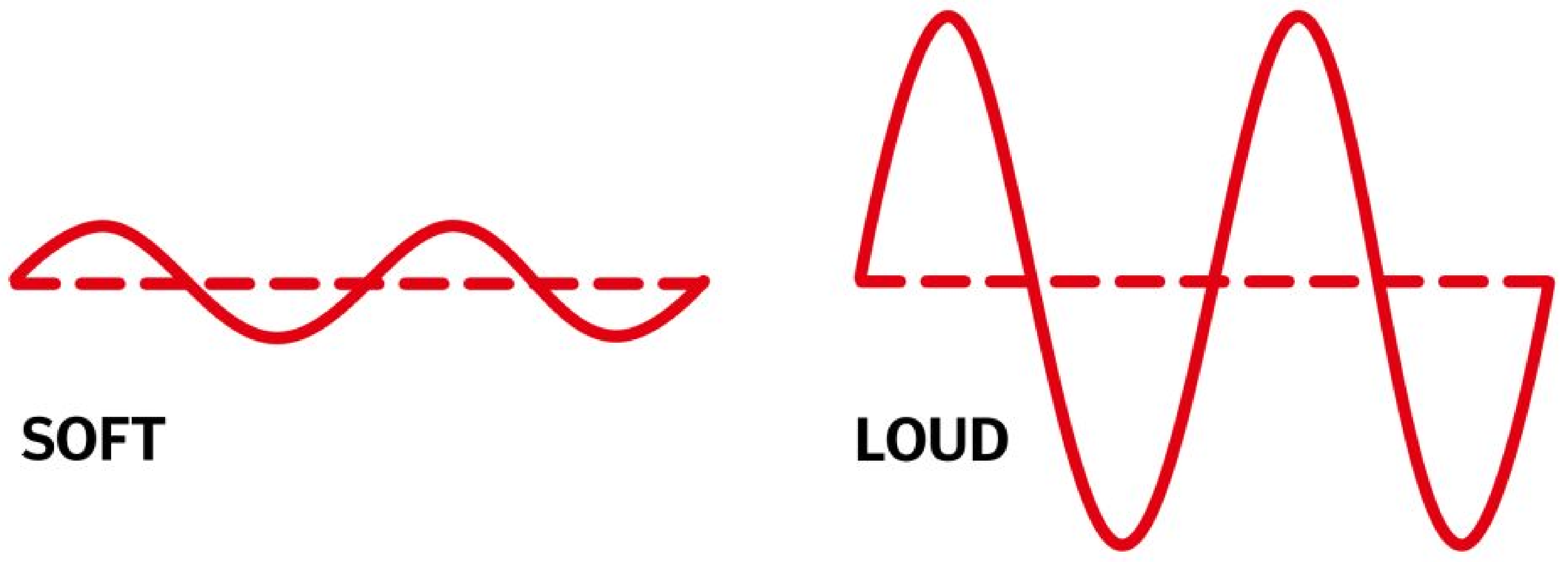
Your brain then has to handle these incoming sounds, and it doesn't just translate the notes into electricity. The processing of music links up with the parts of your brain that control pleasure, fear, movement, memory and emotion, and songs can trip unexpected circuits. We'll show you exactly what goes on in your brain when your favourite song is played.

Waveforms

Changes to the shape of a sound wave alter its properties

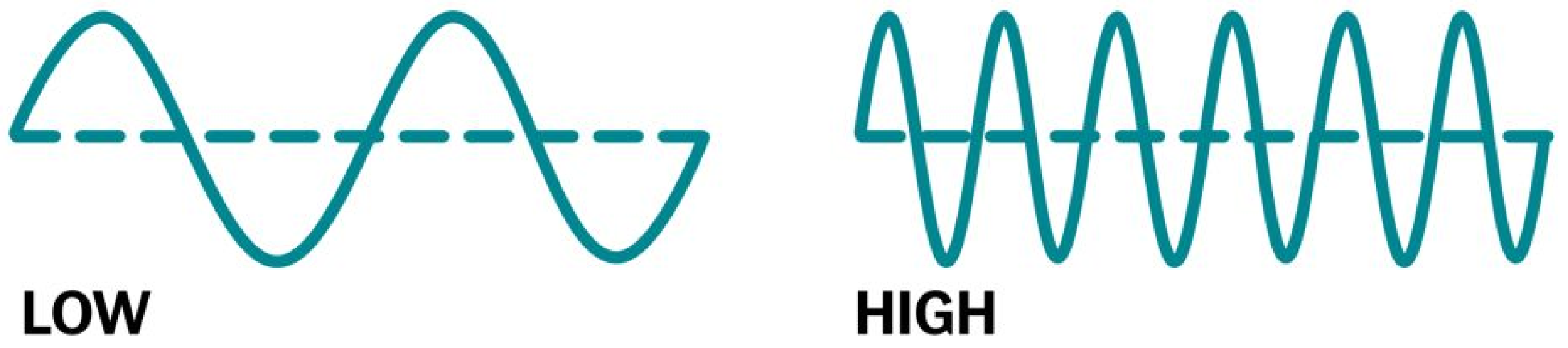
Volume

The loudness of a sound is dictated by the amplitude, or height, of the wave. The bigger the vibration, the louder the sound.



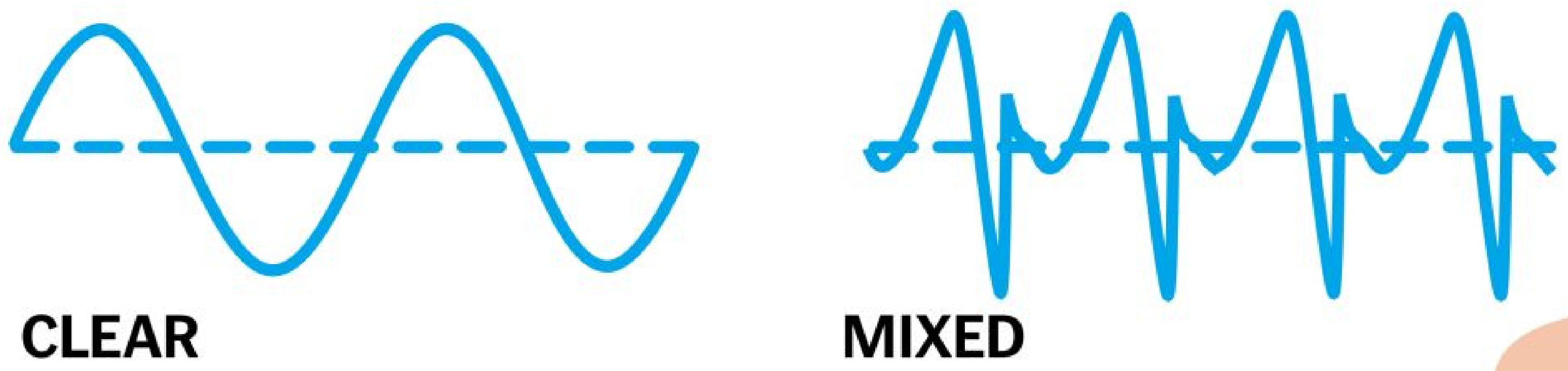
Pitch

Pitch is determined by the frequency of the wave: how often it vibrates in a given time. Low frequency waves produce low notes, while high frequency waves produce high notes.



Timbre

Timbre is the quality or tone of the sound; two instruments can produce the same note, but sound completely different. This property is determined by the sound wave's shape.

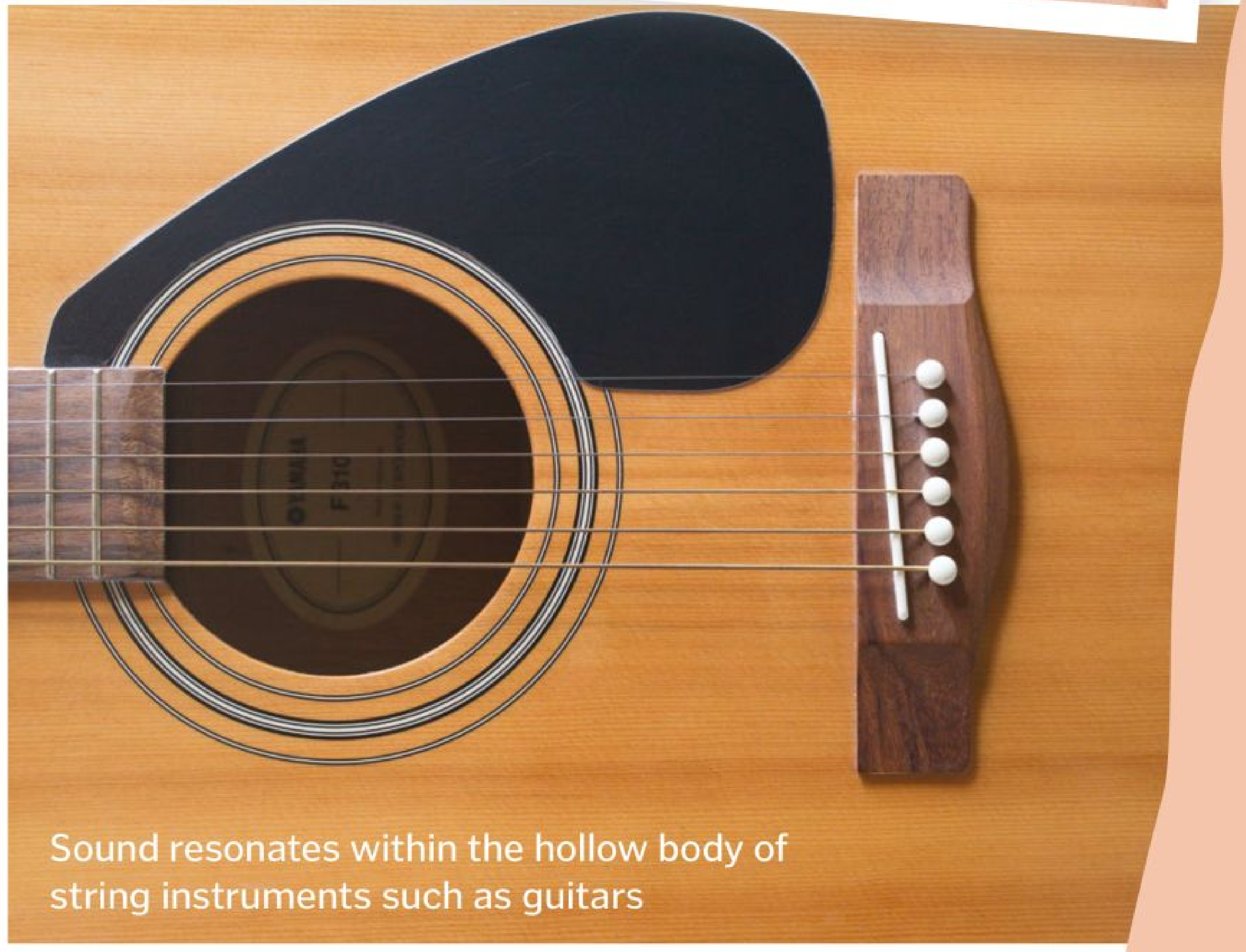


Acoustic resonance

Elastic bands stretched over margarine tubs don't sound the same as steel strings stretched over a guitar. The vibrations created by plucking the band, or the string, are transferred into the body of the instrument, and the shape and materials have a huge impact on the resulting notes. Different objects prefer to vibrate at certain frequencies, and some frequencies are amplified much more than others; this is known as resonance.

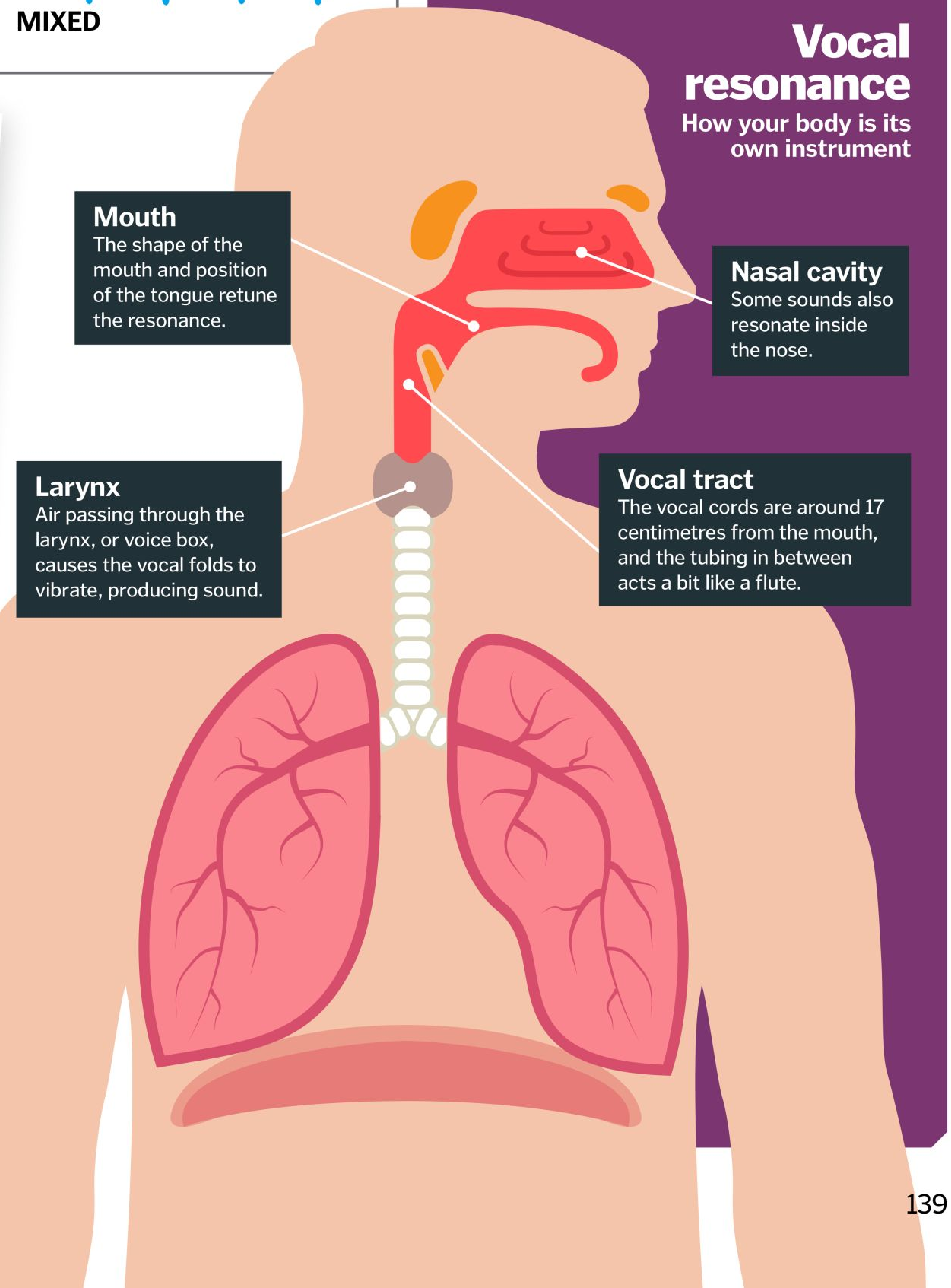
The resonant frequencies of a musical instrument are fixed, unless it can change shape – and this is what makes the human voice so special. The throat, mouth and nose act like the pipes of a musical instrument, amplifying the vibrations made by the vocal folds. Changing the shape of the mouth produces different vowel sounds, and opening the throat or singing through the nose produces completely different tones – this is because we are changing the resonating characteristics of our vocal sound system. Opera singers are experts in resonance, using it to fill a concert hall with their voices without the need for a microphone.

We can change the shape of our vocal cords to produce different tones


Sound resonates within the hollow body of string instruments such as guitars

Vocal resonance

How your body is its own instrument



Mouth
The shape of the mouth and position of the tongue retune the resonance.

Nasal cavity
Some sounds also resonate inside the nose.

Larynx
Air passing through the larynx, or voice box, causes the vocal folds to vibrate, producing sound.

Vocal tract
The vocal cords are around 17 centimetres from the mouth, and the tubing in between acts a bit like a flute.

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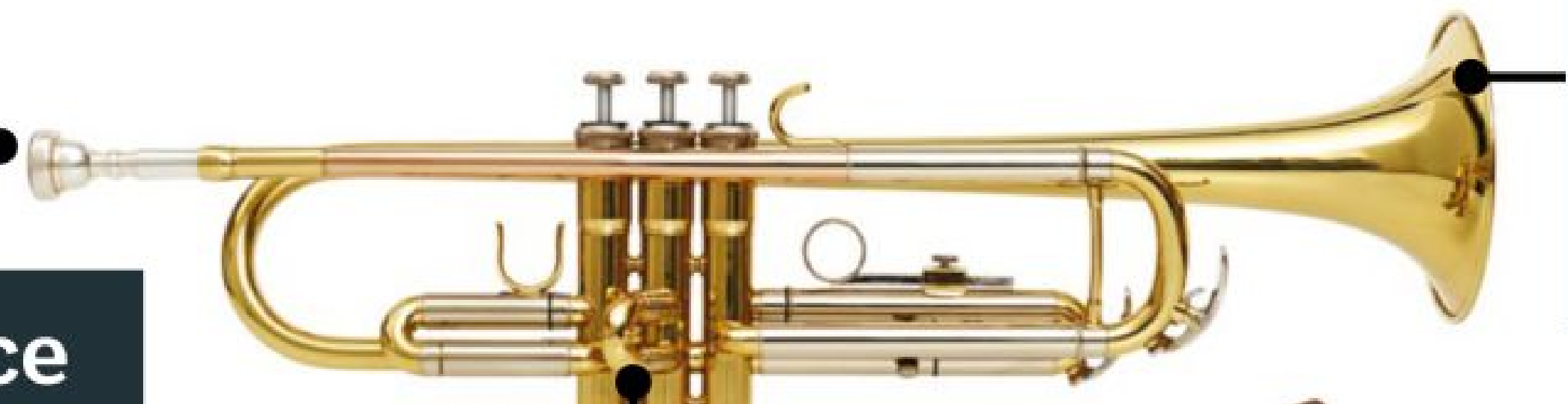
Instruments

The different orchestra sections explained

Brass

Brass players produce sound by buzzing their lips against a metal mouthpiece. The vibration that they produce determines the frequency of the note, and it can be altered by changing the shape of the mouth. The final sound is also influenced by the instruments, and they come in many different shapes and sizes, from a simple tube, all the way up to complex networks with holes, valves and slides. These change the path that the air takes through the pipes, altering the pitch – the further the air travels, the lower the note.



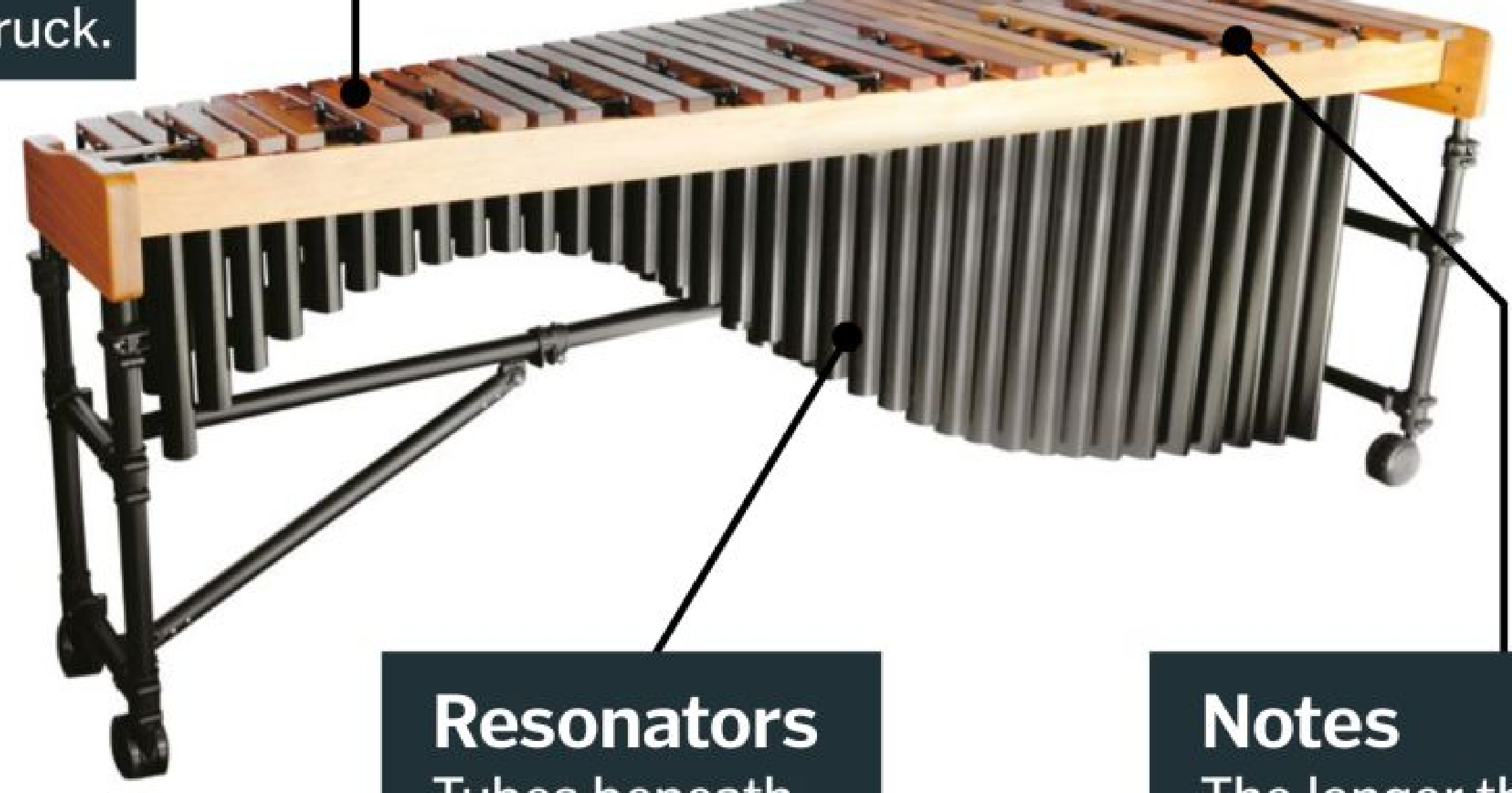
Mouthpiece
The larger the mouthpiece, the lower the sound.

Valve
Slides and valves force the air to take different routes, altering the pitch.

Bell
The flared shape at the end helps to radiate the sound.

Percussion

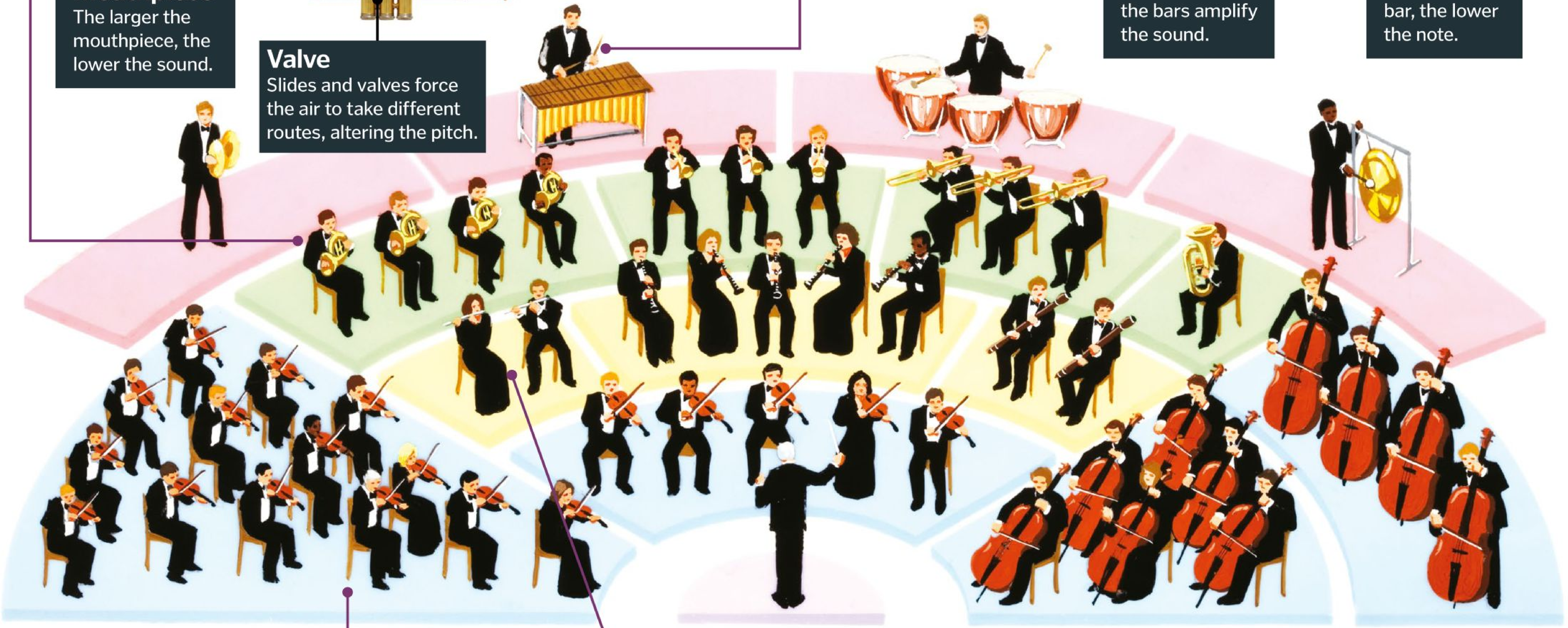
These instruments make a sound when they are hit, and like their more complex siblings, they do this through vibration. With a drum, the vibrations are made when the stretched skin is struck, and the sound is amplified by the shell. With a bell, the clapper strikes the metal, causing the bell and the air inside to vibrate, and with a xylophone, the sound is amplified by tubes beneath the bars. Varying the size, shape and materials of the instruments can produce different notes and tones.

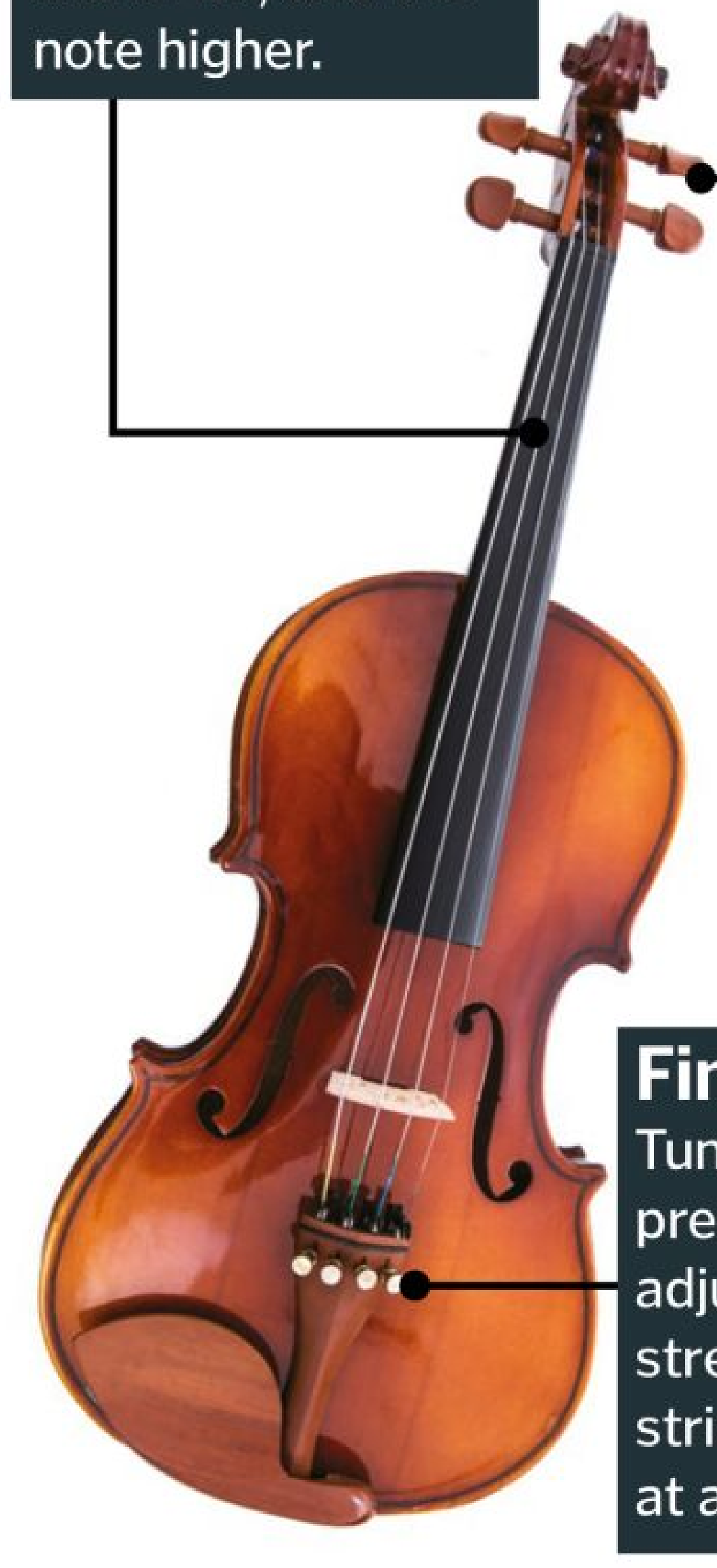


Bars
The bars vibrate when they are struck.

Resonators
Tubes beneath the bars amplify the sound.

Notes
The longer the bar, the lower the note.





Strings
Pressing a finger on the string makes it shorter, and the note higher.

Pegs
The pegs tighten or loosen the strings, changing the pitch.

Fine tuners
Tuning can be precisely adjusted by stretching the string millimetres at a time.

Strings

The strings of a violin, guitar or piano produce different notes depending on their length and thickness. The longer and thicker the string, the lower the sound. The sound also varies depending on the way that the strings are played. A plucked string is tugged against its anchor points, which produces a sharp kink; as it vibrates back and forth, this bend lessens, and the quality of the sound becomes almost instantly smoother. As a bow passes along a string it is continuously vibrated, producing long, sustained notes. And with the hammers of a piano, the strings are struck and then dampened, ending the vibrations to create a crisp sound.

Woodwind

Wind instruments work by creating a column of air that can be lengthened or shortened by covering and uncovering holes in the tube; the longer the column, the more time it takes for vibrations to travel through, and the lower the pitch. There are two main families: flutes and reed instruments. Flutes work in the same way as blowing over the top of a bottle – using a jet of air to make the air inside the instrument vibrate. Reeds are flexible, and when the musician blows, they vibrate and change the flow of air through the instrument.

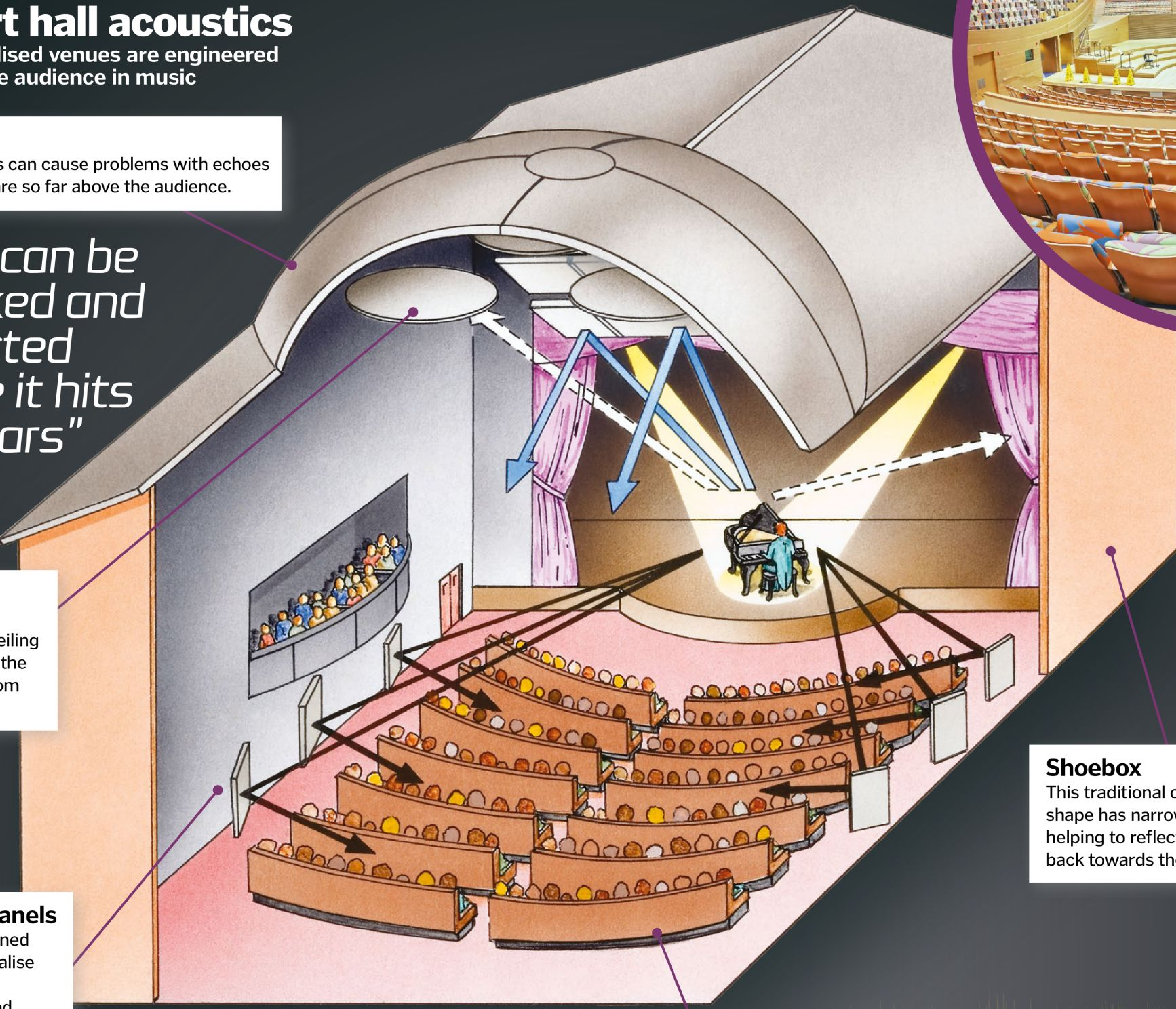
Up an octave
By adjusting their lip position and blowing harder, players can make the air travel faster, producing the same note an octave higher.

Embouchure hole
The jet of air is disturbed by the hole, creating vibrations in the instrument.

Changing notes
Pressing the keys down effectively makes the tube longer, lowering the pitch.

Concert hall acoustics

These specialised venues are engineered to envelop the audience in music



Dome
Domed ceilings can cause problems with echoes because they are so far above the audience.

Anti-echo panels
Panels in the ceiling help to deflect the sound away from the dome.

Acoustic panels
Specially designed structures equalise the sound, and bounce selected frequencies inwards.

Shoebox
This traditional concert hall shape has narrow walls, helping to reflect the sound back towards the audience.

Absorption
The seats and the audience themselves absorb sound, so the room must be designed to compensate for this.

> *"Music can be tweaked and perfected before it hits your ears"*

The panels on the walls and ceilings of concert halls are crucial

Concert hall acoustics

Playing the right notes is only part of the battle

Concert halls have a big job to do. They need to immerse the audience in the sound of the loudest of orchestras without causing echoes, and they need to amplify the most delicate of soloists so that people at the back can hear clearly. There are three factors to consider to make sure the audience enjoys the experience: volume, equalisation and reverberation.

Volume is dictated by the direct sound of the orchestra, but it is also influenced by reflections from the walls and ceiling. For concert halls, it's important not to have too much reflected sound. Your ears expect sound to come from the orchestra, not from the walls behind you.

Equalisation ensures that all frequencies can be heard; different rooms amplify some frequencies more than others. The goal is to balance the sound somewhere in the middle, and to dampen the highest notes a little to avoid any screeching from the strings.

Reverberation is the result of sound bouncing around inside the hall. Surfaces don't reflect all sounds equally, so this can cause some distortion if it's not corrected.

Concert halls balance all of these factors by using different shapes and materials to balance the sound and direct it at the audience. Flat, hard surfaces bounce the sound, soft surfaces absorb it, and rough surfaces scatter the incoming waves. By lining the walls and ceiling with specially designed panels, the music can be tweaked and perfected before it hits your ears.

Improving acoustics

The ceiling of the Royal Albert Hall in London is covered with dangling mushrooms, but it's not infested with damp. The strange structures are there to improve the acoustics. They were installed following tests conducted in the 1960s, and improved again in 2001, and today there are 85 of these fibreglass fungi. The Royal Albert Hall is huge, and the ceiling is domed, so without the mushrooms there would be a long, delayed echo following every note the orchestra played. Even with the mushrooms, a huge orchestra is required to fill the enormous hall with sound.

The Royal Albert Hall uses acoustic mushrooms to reduce the echoes caused by its domed ceiling

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Music has a powerful influence on the brain

Your brain on music

What happens inside your head when you are listening to your favourite tunes?

Brains are complex, as is music, so teasing out the neurological response to melodies is something of a challenge, but researchers across the world have been working to demystify the baffling science behind it.

The first components of music to be processed by the brain are the basic sounds – pitch, length and volume. From this, the brain then teases out melody, and distinguishes between different instruments. This information is then compared to memories, establishing whether the incoming sound is familiar, and revealing any linked emotions. All together, the processing leads to a response, whether that's switching the song off, or starting to dance. And if you move, that feeds back into your brain again, affecting the experience even further.

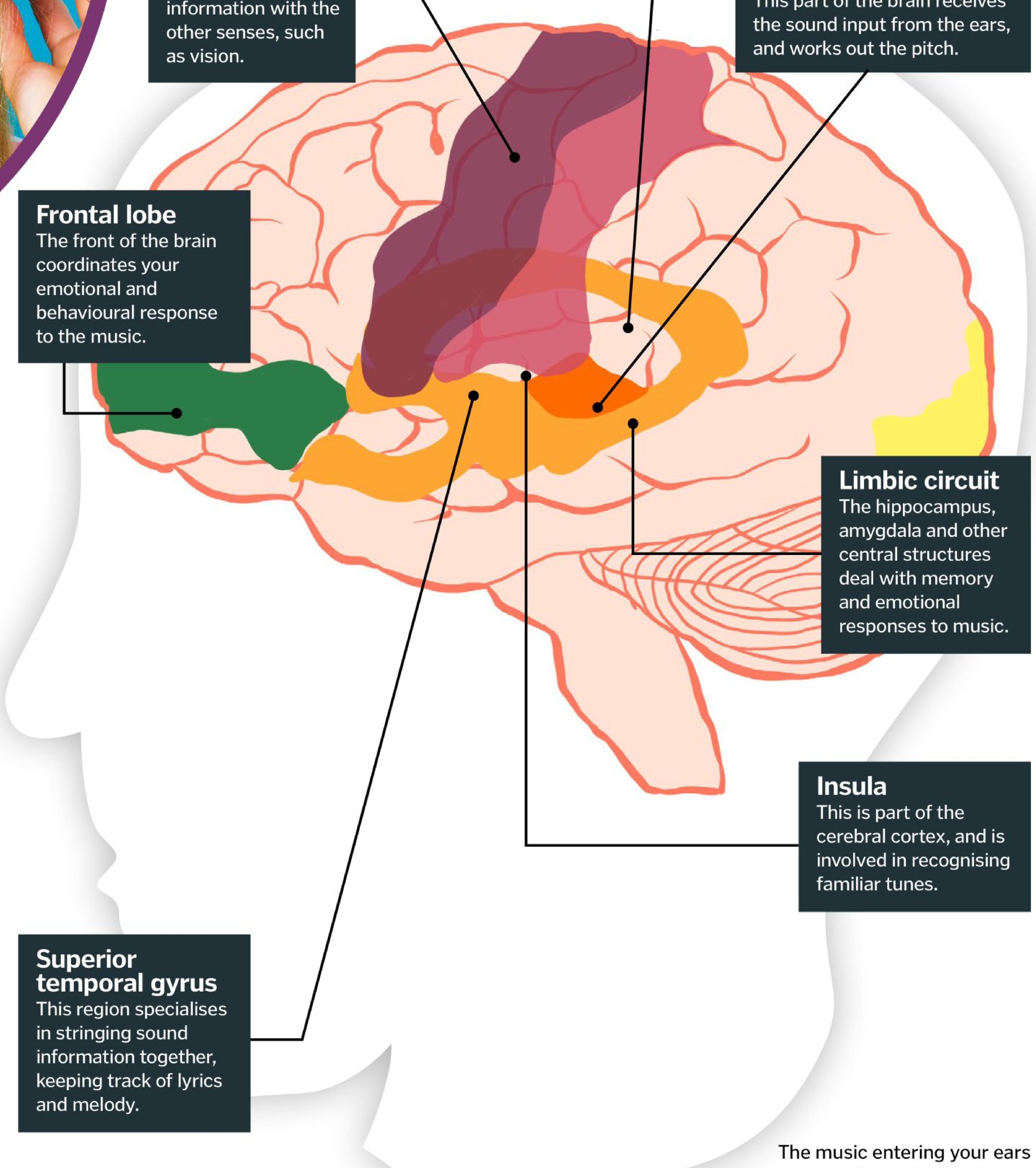
Some of the complexities of the brain's response to music can be revealed by people with damage or injury to their brains. By seeing what happens to the ability to process music after the brain is injured in a certain place, and by observing how that improves as the brain heals, scientists can start to piece together which parts of the brain are involved. This is aided by advanced imaging technology, such as functional MRI scanners, which can monitor the activity in different parts of the brain in response to music.

One major revelation from this kind of work is that music is separate from language. Aphasia is the medical term for a neurological disorder that results in difficulty speaking. It can happen as a result of a brain injury, like a stroke, and makes it challenging for people to find the words that they need to express themselves, but strangely it doesn't always interfere with their ability to sing. Similarly, people with a stammer may struggle with speech but can sometimes sing a song without hesitation.

Around one in 20 people is tone deaf, or 'amusical', and has trouble identifying the notes in a tune. Brain scans have revealed that the white matter in the area involved in processing sound is thinner in these individuals, indicating that it could be less well connected than the same pathways in their musical counterparts.

Processing music

Different areas of your brain come together to handle rhythm, melody, lyrics and emotion



Parietal lobe
This region links incoming sound information with the other senses, such as vision.

Planum temporale
This area deciphers complex sounds, picking out rhythm, timbre and patterns.

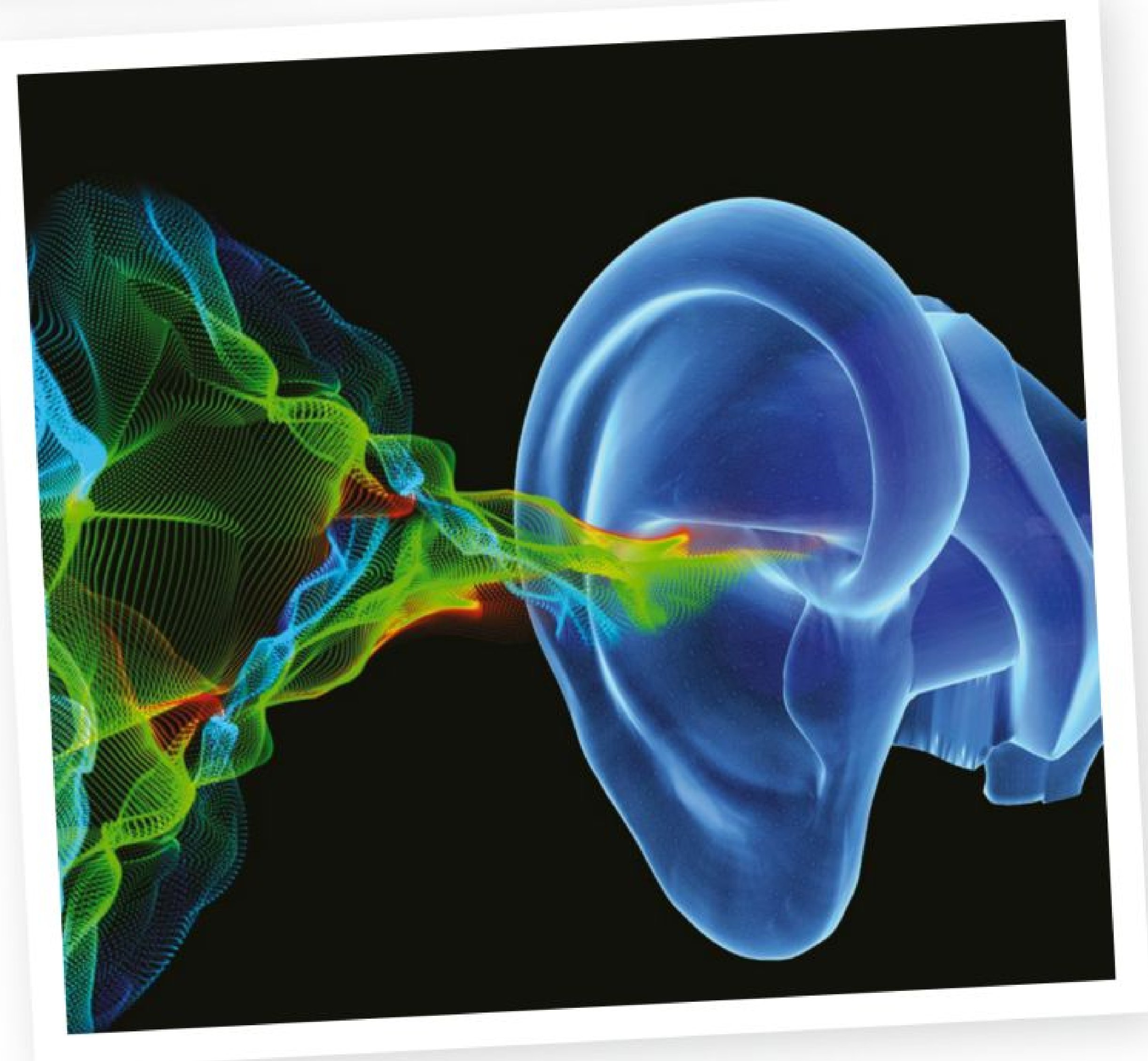
Auditory cortex
This part of the brain receives the sound input from the ears, and works out the pitch.

Frontal lobe
The front of the brain coordinates your emotional and behavioural response to the music.

Limbic circuit
The hippocampus, amygdala and other central structures deal with memory and emotional responses to music.

Insula
This is part of the cerebral cortex, and is involved in recognising familiar tunes.

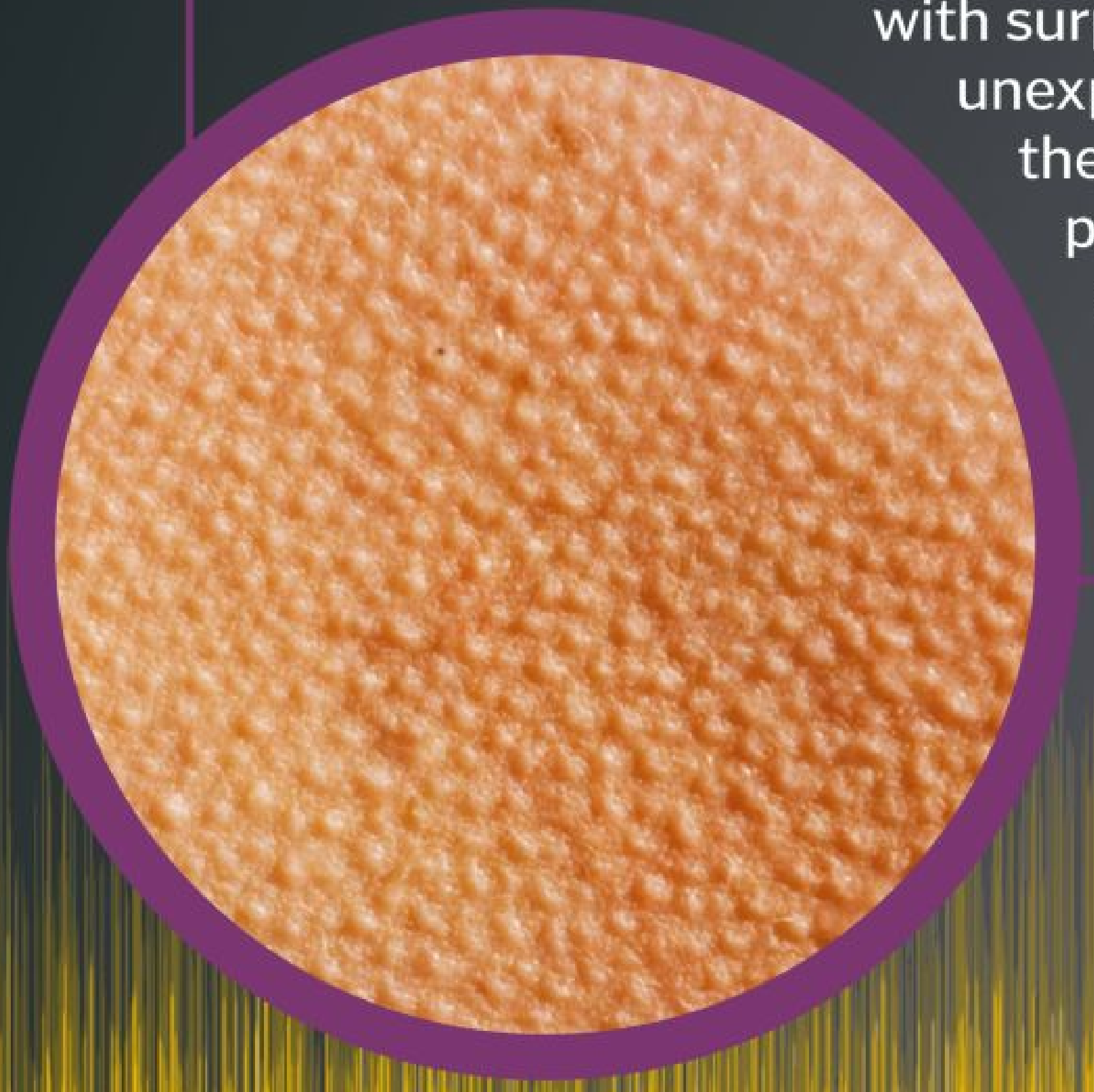
Superior temporal gyrus
This region specialises in stringing sound information together, keeping track of lyrics and melody.



The music entering your ears is just the beginning

Why does music give you 'chills'?

Good songs can make your hairs stand on end, and this is thought to be triggered by the way that our brains are wired. Music taps into the parts of the brain involved with emotion and reward, and listening to certain tunes can light up the same areas tickled by food, and even drugs. At the same time, music seems to decrease the activity in the areas of the brain involved in fear. Getting goose bumps is linked to arousal of your autonomic nervous system, which comes hand-in-hand with an increase in heart rate and deeper breathing. Researchers looking into exactly what triggers this think that it might have something to do with surprise; unexpected shifts in the music are particularly good at setting off this response.



Why do we tap our feet to music?

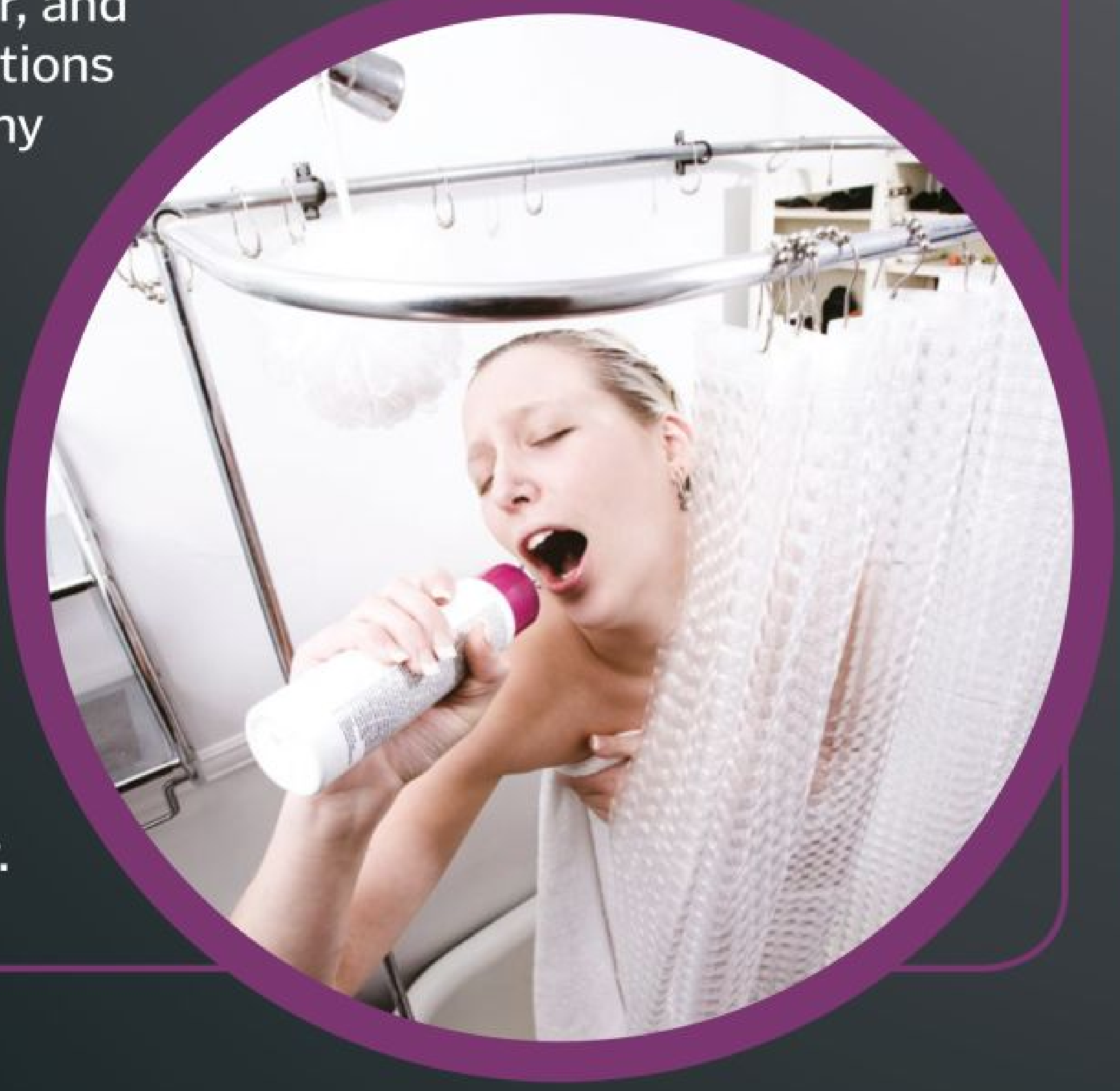
The urge to tap your foot along to a strong beat is often irresistible. It was previously believed that our movements in response to music reflect how we perceive that it was created – a tapping foot imitates a drummer's pedal, for instance – or our mood upon hearing the music. However, more recent research suggests that tapping your foot may influence the way you perceive the music, helping your brain to process what you are hearing.

What makes songs so catchy?

Researchers have an interesting way to describe this phenomenon – they sometimes refer to it as a 'brain itch' or an 'earworm'. Some songs seem to get stuck in people's heads more often than others, but there is not a simple formula that determines catchiness. Researchers working in the field have noticed that catchy songs tend to have short, repetitive sections, and they also often have some connection to the listener. A similarity to a song that you already know, or a cultural connection – such as lyrics that you can relate to – both help to get a tune stuck in your head. Ultimately though, a song that is catchy to one person might not be for another.

Why does your singing sound better in the shower?

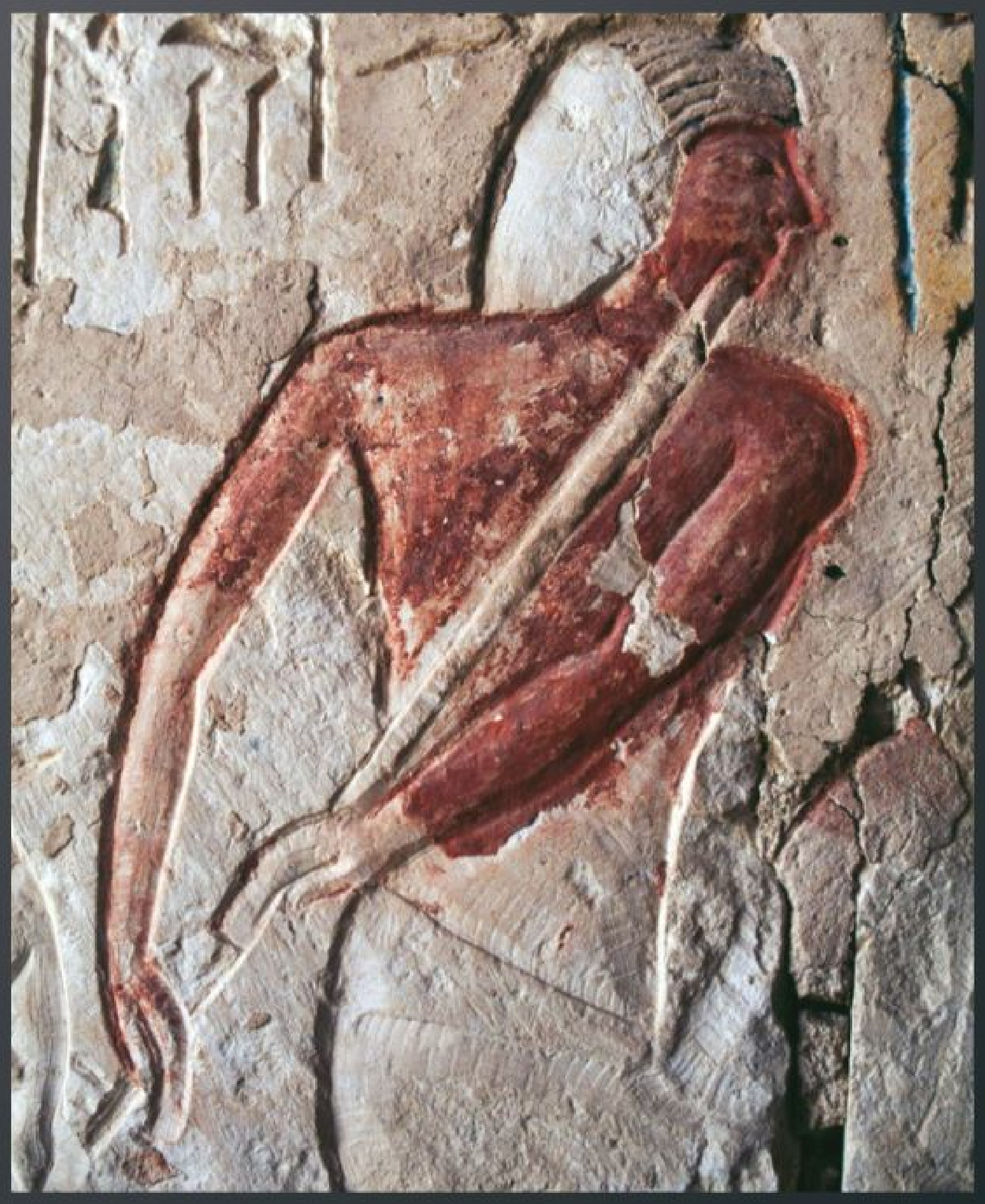
This is down to acoustics. If you sing in a big room with plastered walls, the sound travels a long way before it reaches an obstacle, and a lot of the vibration is absorbed. In a bathroom, the room is smaller, and the tiles or glass reflect the sound back at you in all directions. This creates reverberation. The result is that the sound is louder, and the multiple reflections help to even out any tiny mistakes in your voice. The size of the shower cubicle also has a part to play – lower frequencies tend to be amplified more than higher ones, making the voice sound richer.



> "Around one in every 20 people is tone deaf"

What are the origins of music?

People have been making music for millennia, and the oldest known instruments date back 42,000 years. They are bone and ivory flutes, discovered in a cave in Germany alongside other early human art and ornaments. However, it's generally believed that music was around a long time before the first instruments, as people used their voices to make melodies. Being able to produce music could have helped with social bonding, an idea that is sometimes described as 'vocal grooming'. These kinds of cultural advances are thought to have given our species an edge over our human-like cousins, including Neanderthals.



Music has been a part of human culture for thousands of years

© Thinkstock; Illustration by Rebekka Hearl; Getty

Batteries

Without them our modern lives would be very different indeed

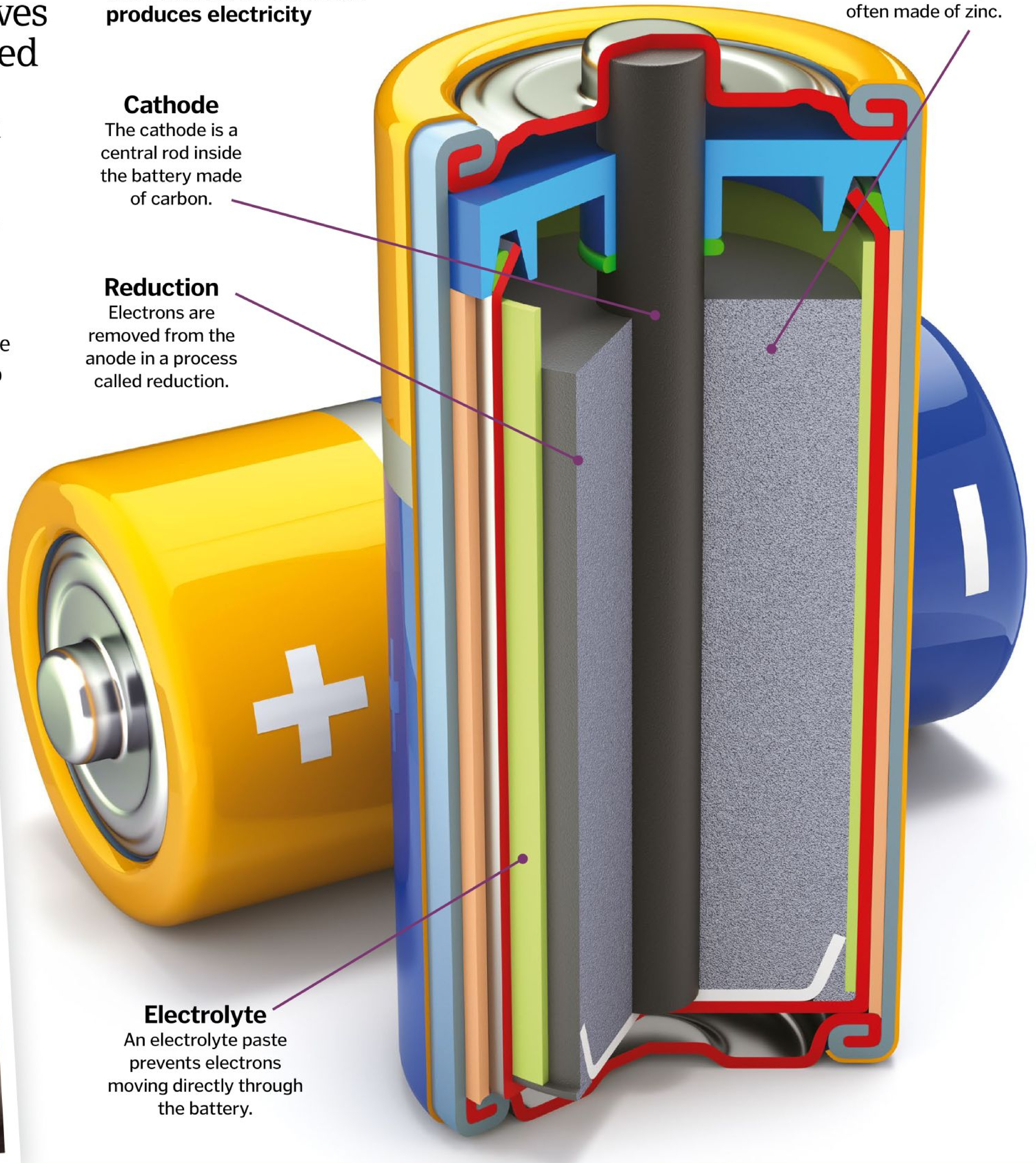
Powering our phones, laptops, cars and more, batteries are modern technological marvels. Their invention dates back to 1800, when Italian scientist Alessandro Volta first came up with the idea of creating a cell that could generate power.

At its heart, a battery involves ferrying electrons between an anode and a cathode. Using an electrolyte – essentially chemical waste – these electrons can't go through the battery, so instead they go around the outside. As they flow around they complete a circuit, and when plugged into a device this flow of electrons provides power.

Different batteries use different reactions and chemicals, such as zinc and alkaline. At their core, though, they all work in the same way.

Inside a dry cell

The flow of electrons from the anode to the cathode produces electricity



Anode
The anode in a dry cell battery is a metal cylinder, often made of zinc.

Cathode
The cathode is a central rod inside the battery made of carbon.

Reduction
Electrons are removed from the anode in a process called reduction.

Electrolyte
An electrolyte paste prevents electrons moving directly through the battery.

Batteries must be specially recycled if you want to get rid of them safely

The Xi particle

How this discovery could open up a new realm of physics

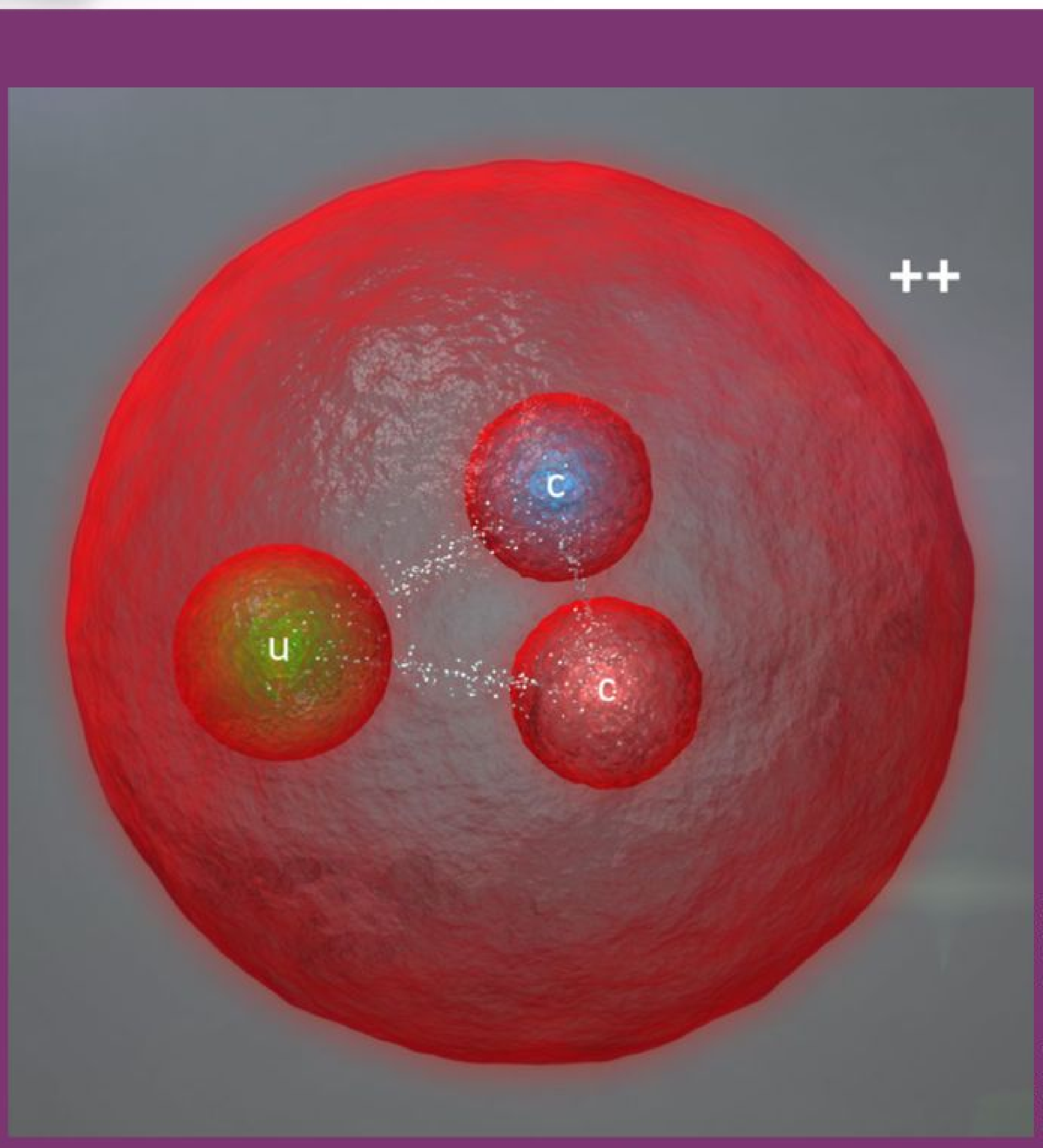
In July 2017, CERN announced the first observation of the Xi particle. This particle had been theorised before but it took the Large Hadron Collider atom smasher to find it.

All particles are made of various subatomic particles known as quarks. This particular particle, technically known as Xi-c-c-plus-plus (Xi_{cc}^{++}), is made up of two charm quarks and one up quark. It is a baryon, the family of particles that includes things like protons and neutrons. All baryons are made of three quarks.

The Xi particle is interesting because it is four-times heavier than a proton. This is because of its two charm quarks, which are 'heavy' quarks, making this the first such particle that has ever been found.

The Xi particle is a bit different from other baryons, where all three quarks dance around each other. In the Xi particle, its two heavier quarks behave like giant stars orbiting each other and the lighter up quark (the lightest of all quarks) orbits around these two.

It's thought that there could be other double-heavy baryons out there awaiting discovery, so the Xi particle has opened the door to some more exotic physics in the future.



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Comprising two charm quarks and one up quark, the Xi particle could help scientists test the laws of the universe

Pressure suits

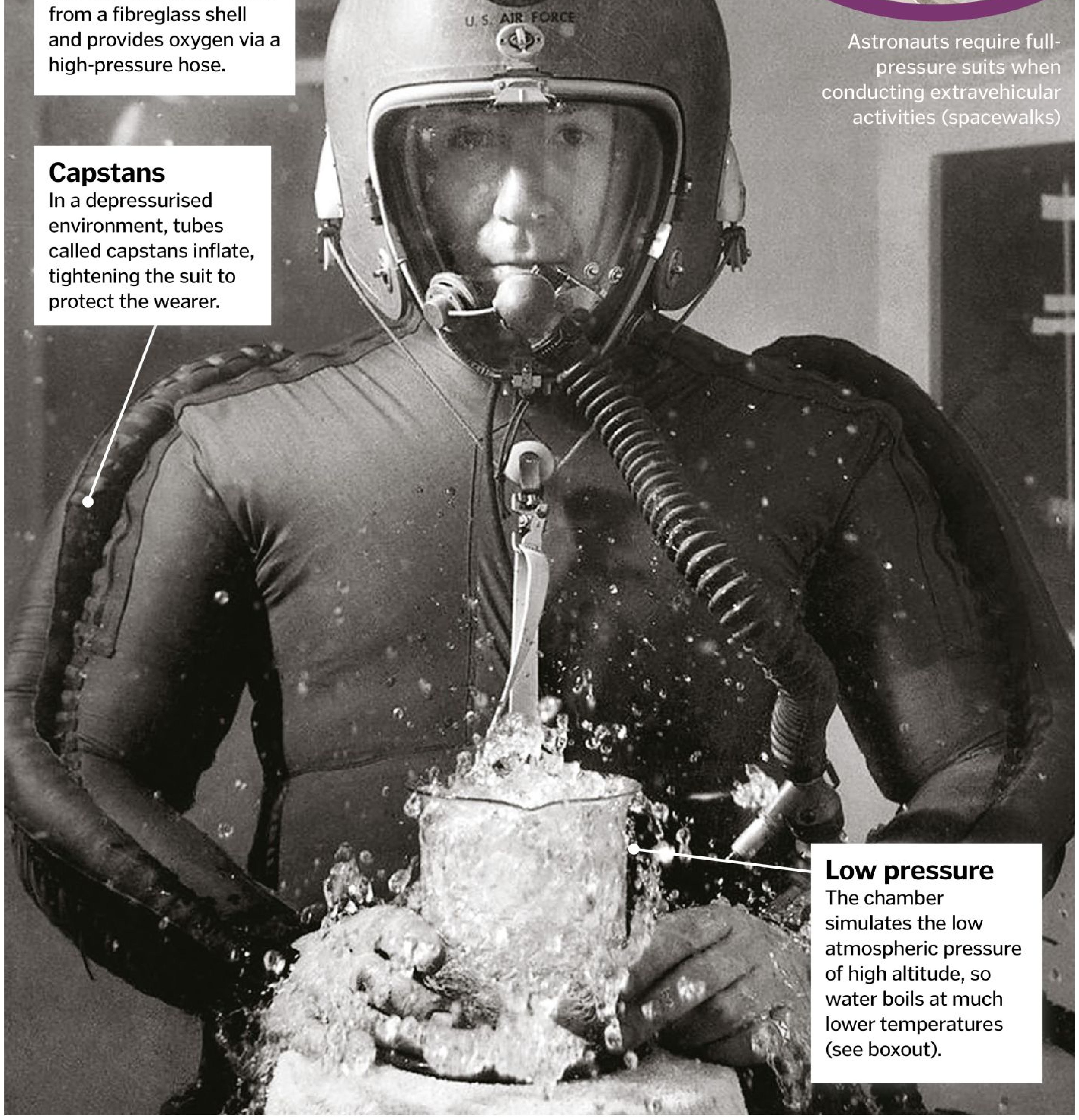
How pressurised clothing enables pilots to soar high up into the atmosphere

At altitudes of 15,000 metres or more both oxygen and pressure levels decrease significantly. The air is so thin that if an aircraft cockpit is depressurised, a pressure suit is needed to survive. There are two types: partial and full. When depressurisation occurs, a partial pressure suit tightens as the capstans, or bladders, that are attached to the suit inflate. Both the sensation and the process are similar to how a cuff feels around your arm when a doctor measures blood pressure. The fabric around the thorax and the major muscle groups is constricted, creating counterpressure that prevents the body from swelling uncontrollably. Pilots can still breathe effectively and move their limbs freely as oxygen is provided through the helmet. It remains tight until the aircraft is able to descend safely to a lower altitude.

Full pressure suits are made from fire-resistant materials like Nomex. Rather than putting actual mechanical pressure on the body, these suits envelop a pilot in a layer of air. This is an artificial atmosphere that the pilot is able to breathe and function in. It's like an air filled balloon surrounding the body. They have anti-g layers built into them, which neutralises the strain exerted on the body by fighter jet manoeuvres and space rocket launches. As this suit doesn't directly pressurise the body, it can be worn for much longer, and some even have straws installed so pilots can eat and drink on long flights without taking off their helmet.

The Model MC-3 pressure suit

A partial pressure suit donned by US Air Force pilots between 1946 and 1989



Helmet
The MA-2 helmet is made from a fibreglass shell and provides oxygen via a high-pressure hose.

Capstans
In a depressurised environment, tubes called capstans inflate, tightening the suit to protect the wearer.

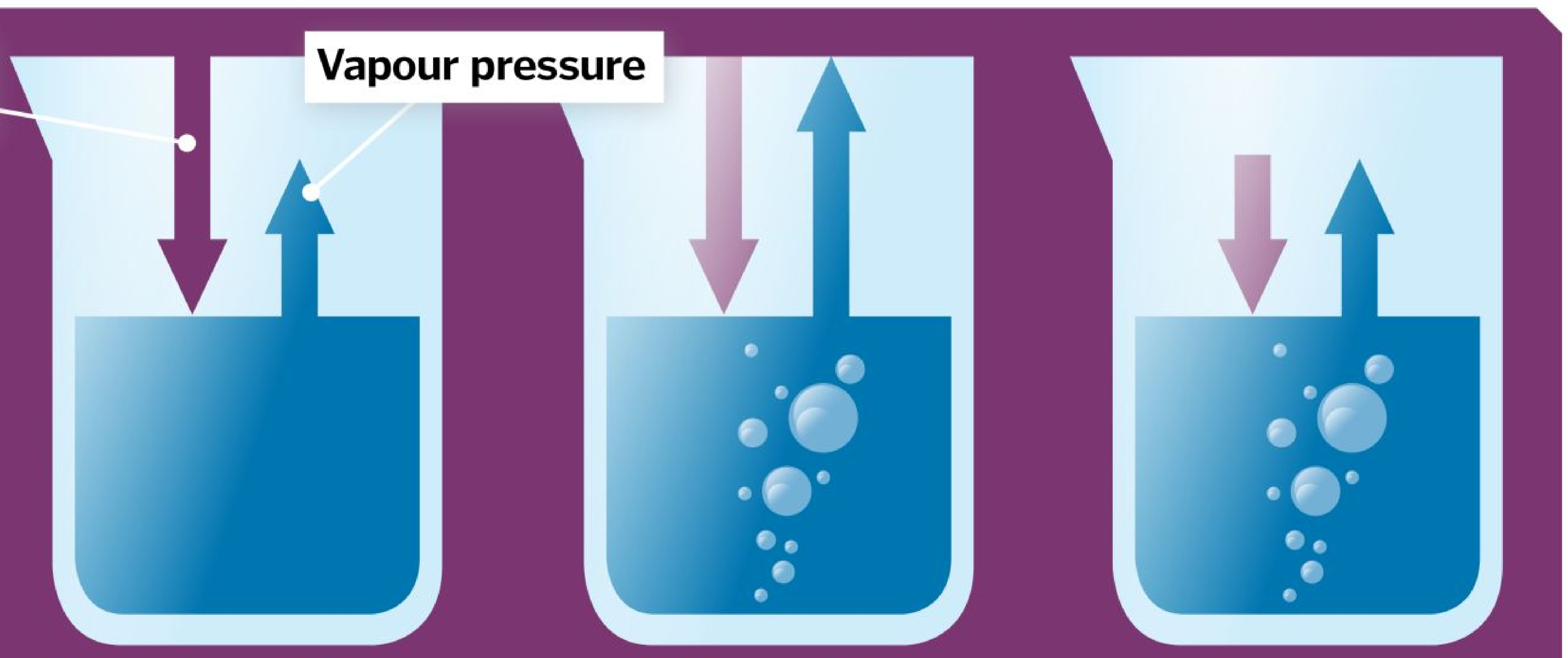
Low pressure
The chamber simulates the low atmospheric pressure of high altitude, so water boils at much lower temperatures (see boxout).

Astronauts require full-pressure suits when conducting extravehicular activities (spacewalks)

Why is the water boiling?

The main image (above) was taken during an experiment by the US Air Force in the 1950s as they were investigating the limits of human flight. It shows a man testing a partial pressure suit in a chamber designed to simulate an altitude of nearly 20,000 metres. But why is the water in the container boiling? This phenomena is a result of the fact that boiling point and atmospheric pressure are linked.

A liquid will boil when its vapour pressure (the tendency of its molecules to escape the liquid's surface to become a gas, which increases with temperature) is equal to atmospheric pressure. Therefore the lower the atmospheric pressure, the less energy (and so a lower temperature) is required for a liquid to boil. For example, water boils at 100 degrees Celsius at sea level, but if you were to climb to the top of Everest, you'd find that water boils at just below 70 degrees Celsius.



Normal conditions
At room temperature at sea level, water doesn't boil because the vapour pressure is lower than the atmospheric pressure.

Boiling point
At sea level, raising water temperature to 100°C increases its vapour pressure to equal atmospheric pressure, boiling it.

Low pressure
Under low pressure conditions, liquids boil at lower temperatures because less energy is required for the water to vapourise.

© WIKI; NASA

How knives cut

The cutting-edge science behind chopping up food

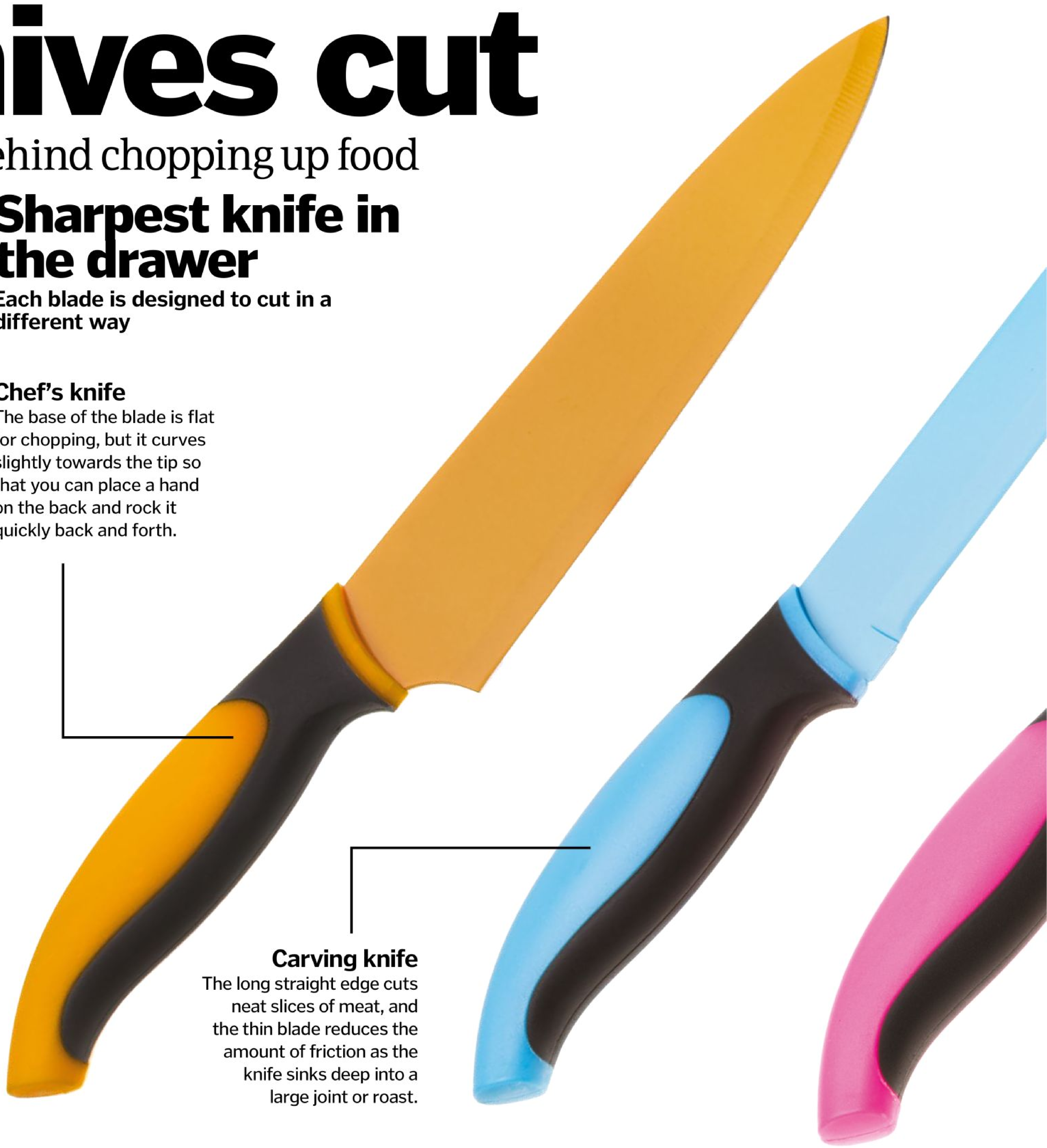
Imagine pushing your hand down flat on a block of butter; some of it will squish out on either side of your hand, but you have to work quite hard because you are mostly pushing the butter down, not sideways. Now try again with your hand vertical, as if you are performing a karate chop. This time it is easier to make a dent, because your contact area with the butter is smaller so you don't need to push so much of it downwards.

Like your vertical hand, a knife is a wedge. It converts the downward force you put on it into sideways force that separates an object into two halves. The sideways force stretches the bonds that hold the object together until the molecules are so far apart that the bonds are snapped. The thinner the knife edge, the easier it is to start off the process and this corresponds to the sharpness of the blade.

The angle of the wedge also makes a difference. An axe blade has a shallow angle that converts a lot of the downward motion of the axe into sideways force against the wood. This is essential as wood is very springy and the fibres must be forced a long way apart before they will split. However, for something delicate like raw fish, or a tomato, you need a very acute angle on the blade. Too much sideways force will crush the rest of the flesh. If you try to cut a tomato with an axe, you will make a mess, no matter how sharp the axe is.

Sharpest knife in the drawer

Each blade is designed to cut in a different way



Chef's knife

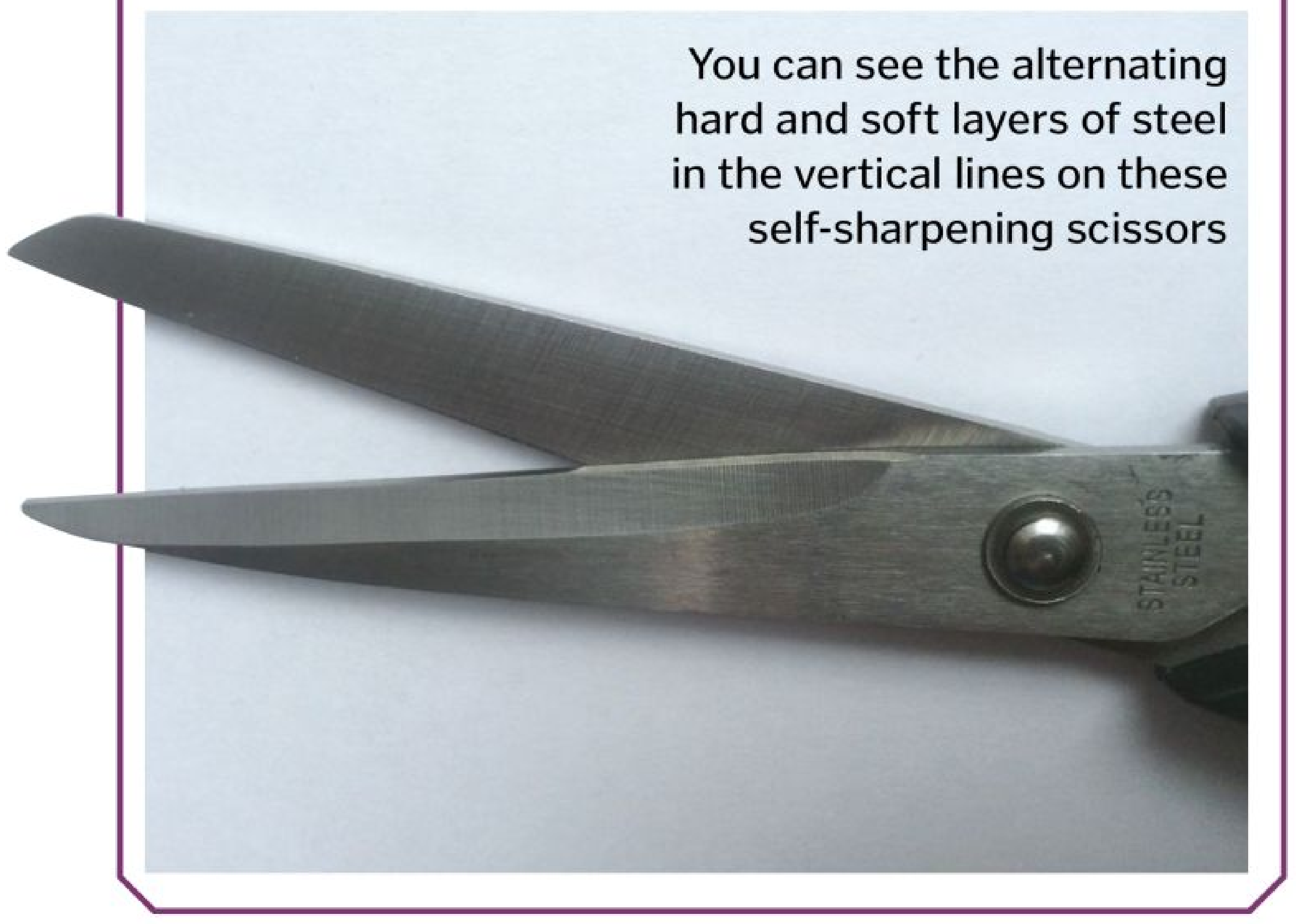
The base of the blade is flat for chopping, but it curves slightly towards the tip so that you can place a hand on the back and rock it quickly back and forth.

Carving knife

The long straight edge cuts neat slices of meat, and the thin blade reduces the amount of friction as the knife sinks deep into a large joint or roast.

Self-sharpening blades

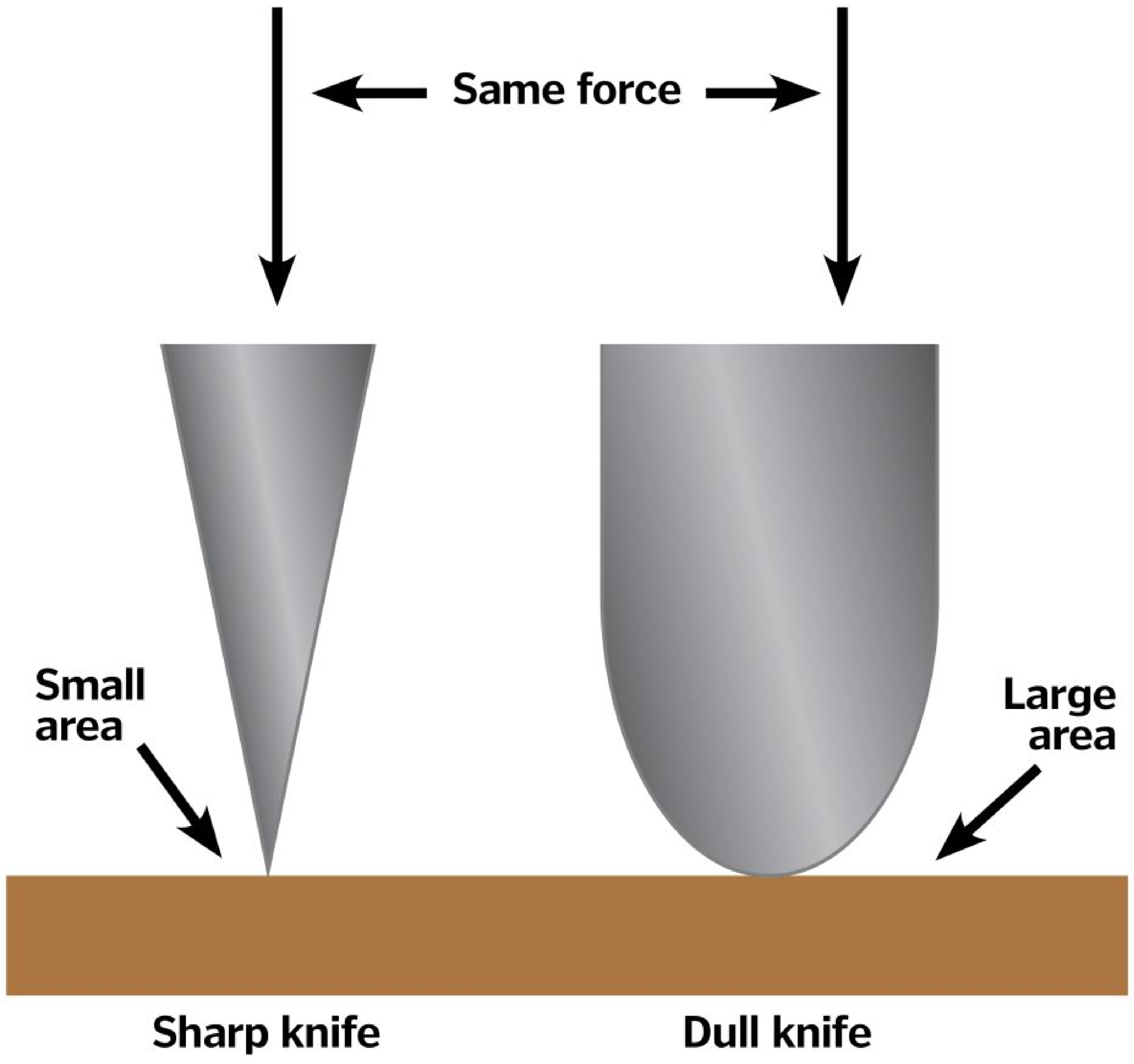
Some knife sets incorporate a grinding stone in the knife block so that each blade is sharpened as you push it back into its slot. But a truly self-sharpening blade is built from alternating layers of hard and soft steel, or steel that has a crystal 'grain', comprising hard and soft layers. As the blade saws back and forth, the hard layers grind down, but the softer layers in between wear faster, so the blade always presents a saw-tooth profile of hard points.

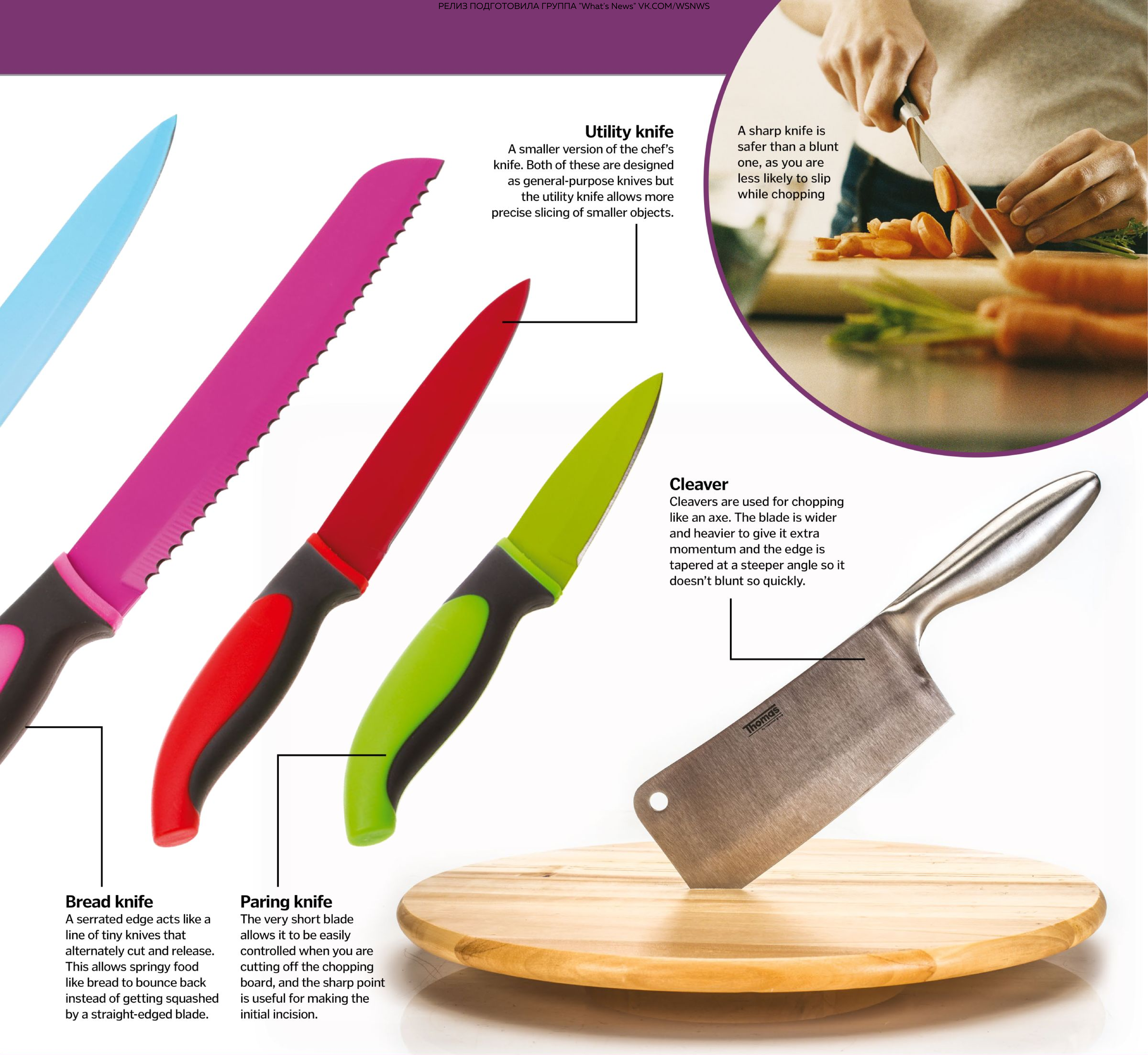


You can see the alternating hard and soft layers of steel in the vertical lines on these self-sharpening scissors

Magnifying force

Just as a magnifying glass concentrates the light from a wide lens into a narrow spot at the centre, a knife concentrates the force from your hand and arm into a thin line at the blade's edge. The sharper a knife, the narrower the contact area at the cutting surface. Since pressure is equal to the force divided by the area, a smaller contact area produces a higher cutting pressure from the same amount of force. This high pressure makes it easier to push the blade into the object you are cutting. However, sharp blades have delicate edges that wear away more quickly, so they need regular re-sharpening.





Utility knife

A smaller version of the chef's knife. Both of these are designed as general-purpose knives but the utility knife allows more precise slicing of smaller objects.

A sharp knife is safer than a blunt one, as you are less likely to slip while chopping

Cleaver

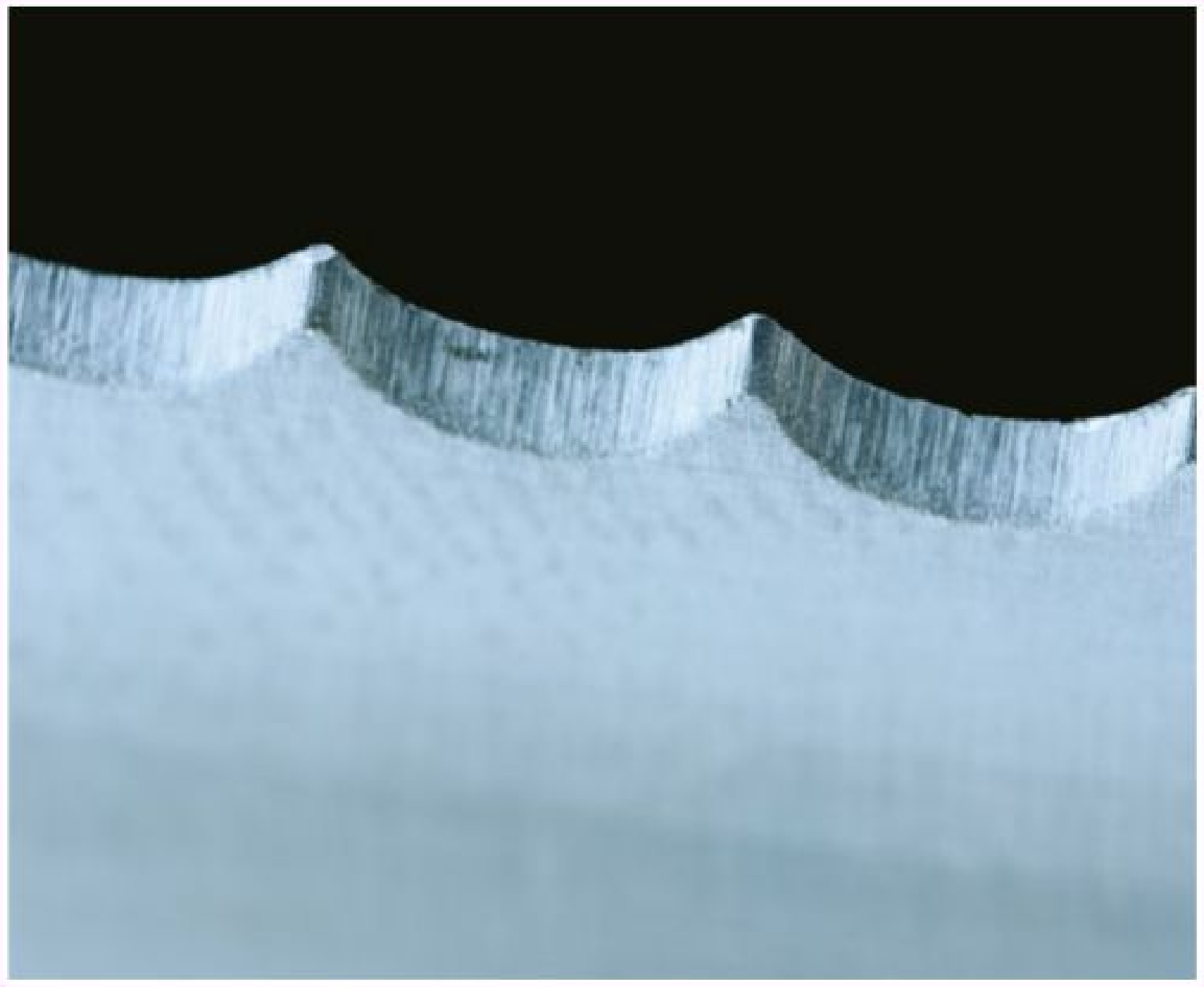
Cleavers are used for chopping like an axe. The blade is wider and heavier to give it extra momentum and the edge is tapered at a steeper angle so it doesn't blunt so quickly.

Bread knife

A serrated edge acts like a line of tiny knives that alternately cut and release. This allows springy food like bread to bounce back instead of getting squashed by a straight-edged blade.

Paring knife

The very short blade allows it to be easily controlled when you are cutting off the chopping board, and the sharp point is useful for making the initial incision.



High-carbon steel

This super-tough steel traps carbon atoms in the crystal structure, which makes it much harder than ordinary iron.

Stainless steel

This iron alloy has chromium added to it, which stops it from rusting but also makes it softer, so it blunts quicker.

Ceramic

Zirconium dioxide, or zirconia, is much harder than steel and doesn't need sharpening, but it can chip or snap.

Glass

Glass fractures with much sharper edges than any metal. Laboratory researchers use glass knives to prepare microscope samples.

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Boomerang science

The secret to the strange flight path of a boomerang is in its wings

A stick will tumble through the air in a relatively straight line before crashing to the ground, but a boomerang curves in a wide arc and comes right back to your hand. The key is in its shape.

Boomerangs have two wings, each with an aerofoil design: one side is flat, and the other side curved. This shape changes the flow of air across the aerofoil, creating a difference in pressure above and below it, which generates lift. But this is only part of the story.

The placement of the wings is the secret to getting the boomerang to return. The sharp, leading edge of each wing face the same way, turning the curved stick into a kind of propeller.

Boomerangs are thrown upright, and as they leave the hand they start to spin. As they travel through the air, the top wing spins forwards, moving in the same direction as the throw, while the bottom wing turns backwards, moving against it. The combination of the spin and throw mean that the top wing moves faster than the bottom, and as this happens, the boomerang starts to tilt. The effect is called precession.

The boomerang has angular momentum and spin, and it will try to keep spinning in the same direction unless a force is applied. But the fast-moving top wing pushes it out of line. The boomerang leans to the side, turning full circle before coming back to where it was thrown.

Do all boomerangs come back?

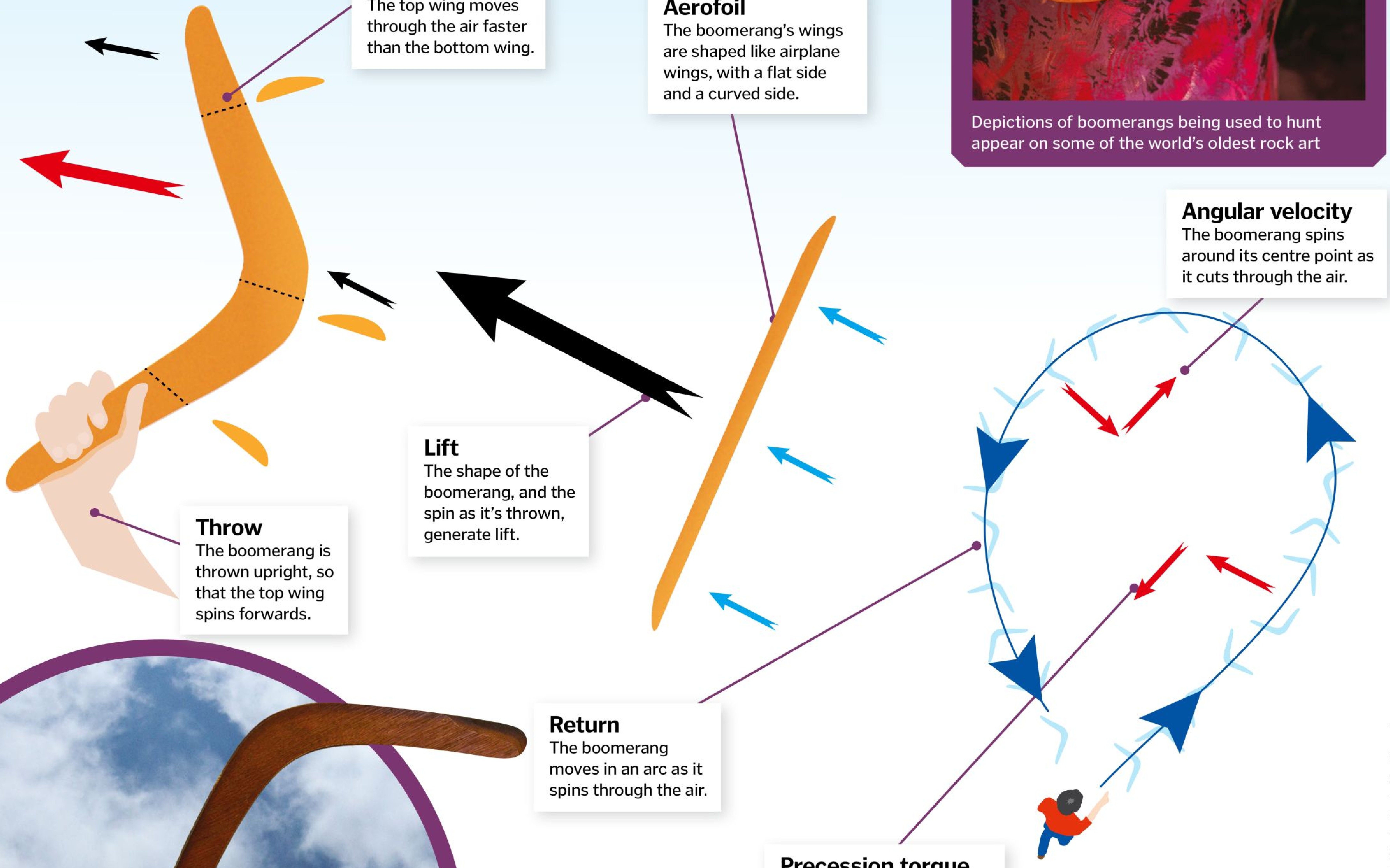
Boomerangs are famous for coming back to their owners, but though this feature is interesting, it's not very practical. Returning boomerangs are toys, but the original boomerangs were hunting weapons, and flying through the air in a wide arc would make them difficult to aim.

Hunting boomerangs aren't designed to come back. They are precision throwing weapons, constructed to be bigger and heavier and to stop when they strike their target. Rather than having two equally curved arms, one side is often longer than the other, helping them to cut through the air quickly and accurately.

Depictions of boomerangs being used to hunt appear on some of the world's oldest rock art

Flight path

What happens to a boomerang as it flies through the air?



Leading edge
The top wing moves through the air faster than the bottom wing.

Aerofoil
The boomerang's wings are shaped like airplane wings, with a flat side and a curved side.

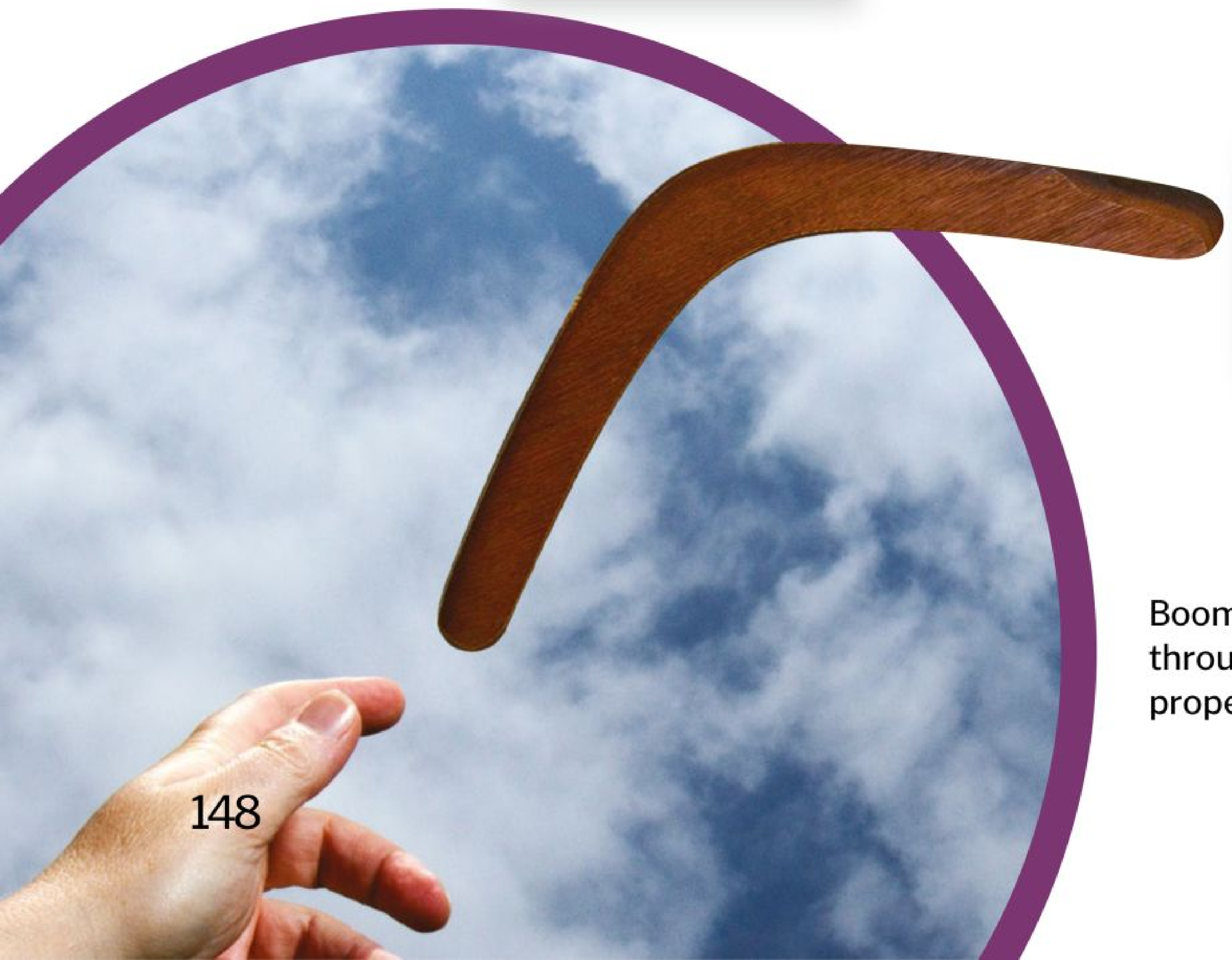
Angular velocity
The boomerang spins around its centre point as it cuts through the air.

Lift
The shape of the boomerang, and the spin as it's thrown, generate lift.

Throw
The boomerang is thrown upright, so that the top wing spins forwards.

Return
The boomerang moves in an arc as it spins through the air.

Precession torque
The difference in air flow over the top wing compared to the bottom causes the boomerang to twist.



Boomerangs spin through the air like the propellers of a helicopter

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The physics of dance

Ballet dancers perform a precise balancing act every time they take to the stage

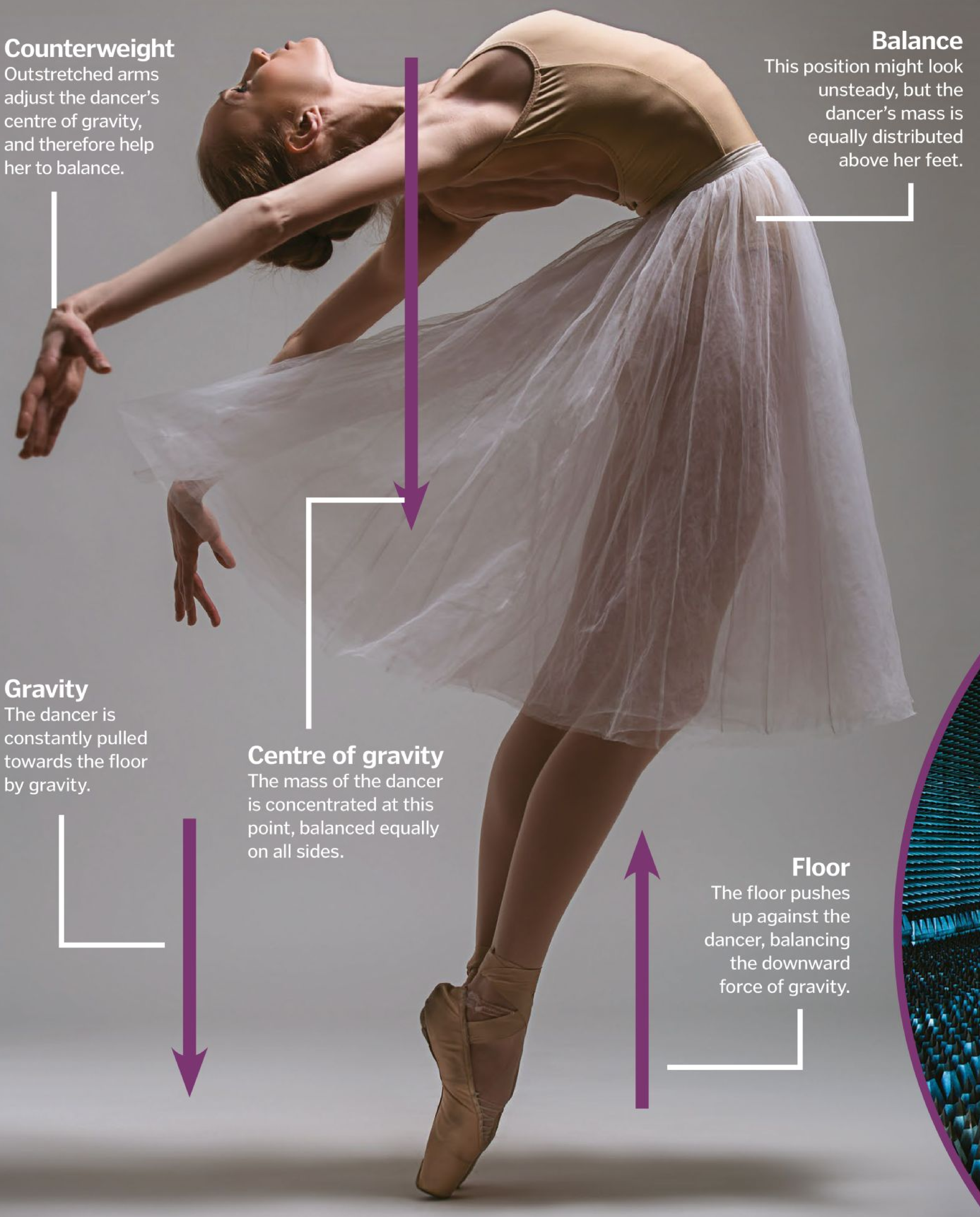
Gravity pulls ballet dancers downwards, while the floor pushes up, counteracting and balancing the force. But balanced forces don't necessarily mean a balanced dancer. Mass is the overall amount of matter that the dancer has inside their body, and to stay on their feet, they need to ensure that the centre point of that mass remains right above the spot where their feet touch the floor.

If the dancer were spherical, their centre of mass would be smack in the middle, making balancing easy. But they have a head, arms and legs, and each time they move, their centre of mass moves too. This makes balancing more challenging, but by using their limbs as counterweights, dancers can stay upright in the most incredible poses.

The dancer's feet in contact with the floor also generate another force: friction. This stops them slipping as they move, and it can also be used to generate torque, or spin. During spins, arms and legs can be used to stunning effect. Thanks to the law of conservation of angular momentum, if a dancer brings their arms and legs inwards during a spin, they will spin faster. Bringing them out again can slow the dancer down to a gentle stop.

Ballet forces

Dancers work hard to keep their centre of mass in line with the floor



Counterweight
Outstretched arms adjust the dancer's centre of gravity, and therefore help her to balance.

Balance
This position might look unsteady, but the dancer's mass is equally distributed above her feet.

Gravity
The dancer is constantly pulled towards the floor by gravity.

Centre of gravity
The mass of the dancer is concentrated at this point, balanced equally on all sides.

Floor
The floor pushes up against the dancer, balancing the downward force of gravity.

The quietest place on Earth

The extraordinary rooms that make it possible to hear your own heartbeat

You haven't truly experienced silence until you've been in an anechoic chamber. These rooms are made from heavy concrete with rubber-sealed doors to prevent any sound at all from getting in. Inside, the walls are covered in foam wedges to absorb internal noise, and the floor is a suspended mesh to eliminate the sound of footsteps. Every inch is designed to absorb reflections of sound waves, so you hear absolutely nothing.

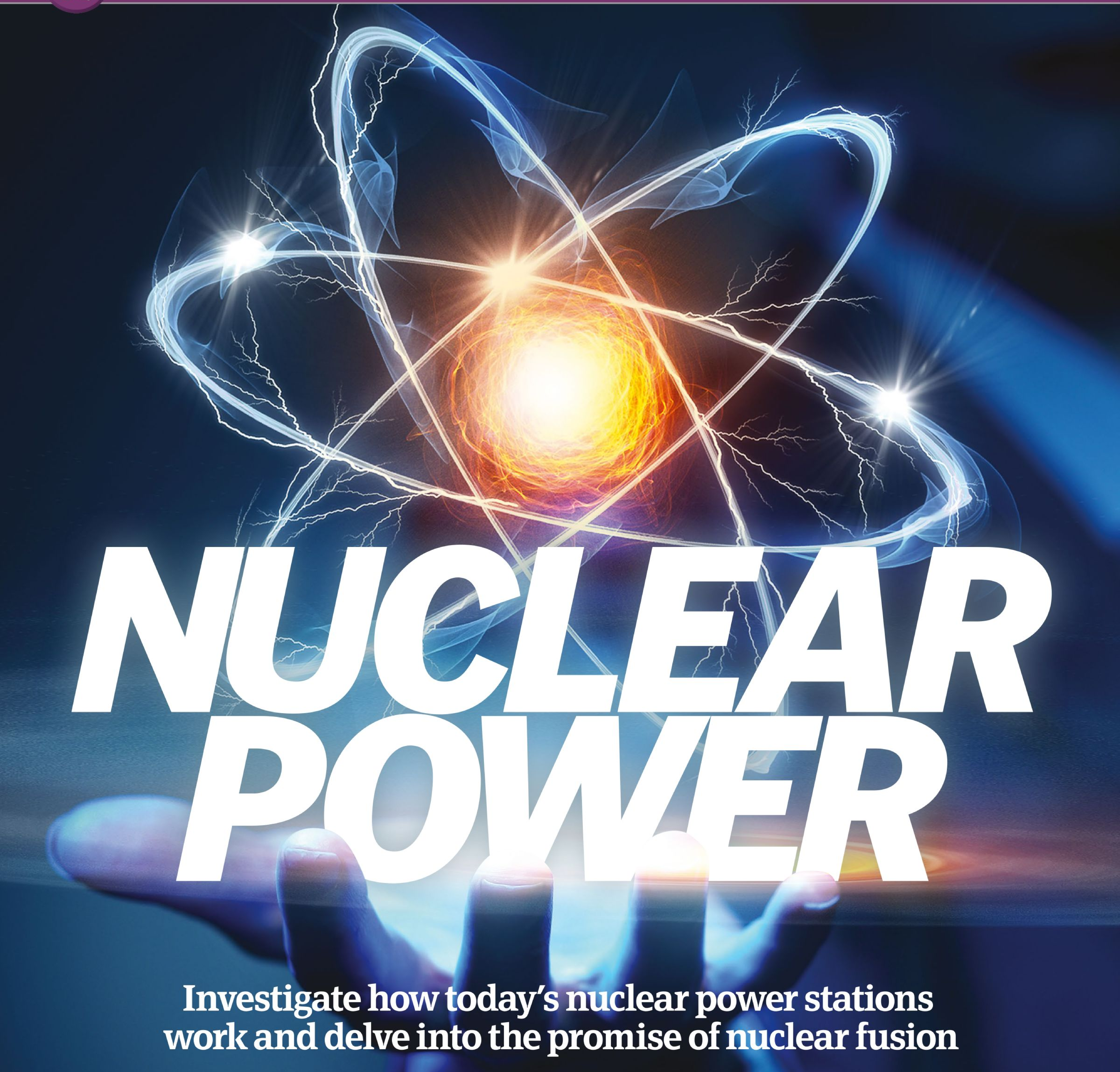
These chambers are mainly used to test the performance of speakers, microphones and other products, but they also help astronauts to prepare for the eerie silence of space. The longest anyone has been able to bear the quiet for is 45 minutes.

Orfield Laboratories, which is in the US, currently holds the Guinness World Record for the quietest place on Earth, as the walls can absorb 99.9 per cent of sound.

In this environment, all a person can hear is the thumping of their heart, which can quickly drive them crazy, and with no perceptual cues to help them balance, it's also incredibly disorientating and difficult to stand or move. So next time you wish for a bit of peace and quiet, think again.

Anechoic chambers absorb all sound so there are no echoes

© Dreamstime



NUCLEAR POWER

Investigate how today's nuclear power stations work and delve into the promise of nuclear fusion

The idea of harnessing energy from nuclear reactions to generate electricity is over 60 years old. Following a slow-down in the 1970s, nuclear power is now on the rise again, partially in response to concerns over the harmful effects of burning fossil fuels. Today's commercial nuclear reactors generate energy from the process of nuclear fission, and we'll investigate what that means, why it generates so much energy and how a nuclear power station works. However, while fission is a tried and proven technology, many scientists believe that the future is one of nuclear fusion. Over the next few pages, we'll take a look at that process to see how it differs from fission and how far we are from generating power from this potentially abundant energy source.

Chemical bonds contain a large amount of energy, which can be released by chemical reactions. Burning fossil fuels is a classic example, and the amount of energy that can be produced this way is evident if we think about how far a car can travel when a gallon of petrol is oxidised. But the amount of energy stored in chemical bonds is tiny compared to the amount of energy that is stored in the bonds between the protons and neutrons in the nucleus of an atom.

It is this energy that is released in the nuclear reactions that take place in nuclear power plants, and the benefit compared to burning fossil fuels is staggering. Weight for weight, fission of nuclear fuel can produce 2-3 million times more energy than burning coal or oil.

Fission vs fusion

Fission and fusion are opposite nuclear reactions, but both can generate energy

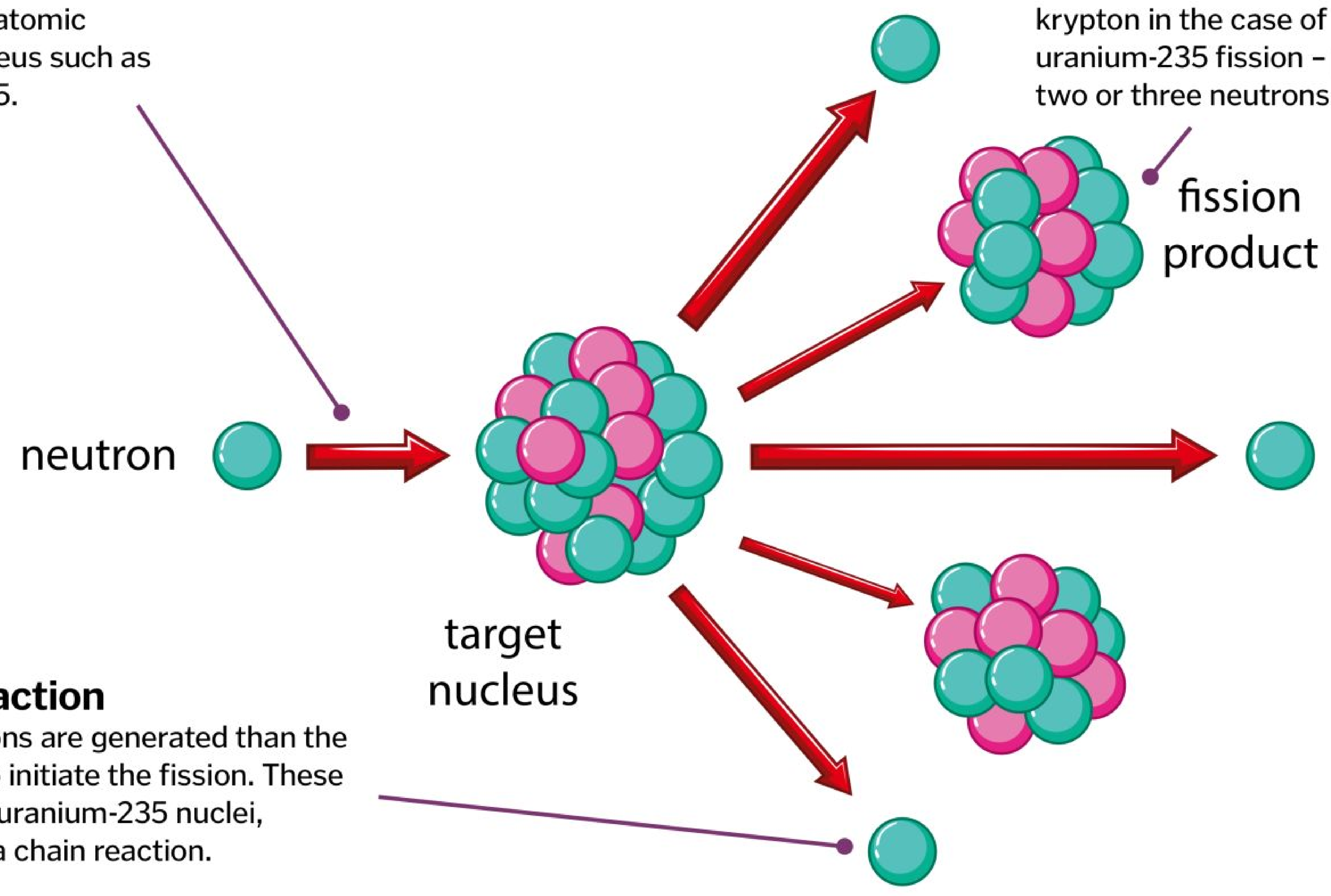
FISSION

Fission reaction

Fission is brought about when a neutron collides with a high atomic weight nucleus such as uranium-235.

Fission products

The result is two smaller nuclei – often barium and krypton in the case of uranium-235 fission – plus two or three neutrons.



Chain reaction

More neutrons are generated than the one taken to initiate the fission. These reach other uranium-235 nuclei, resulting in a chain reaction.

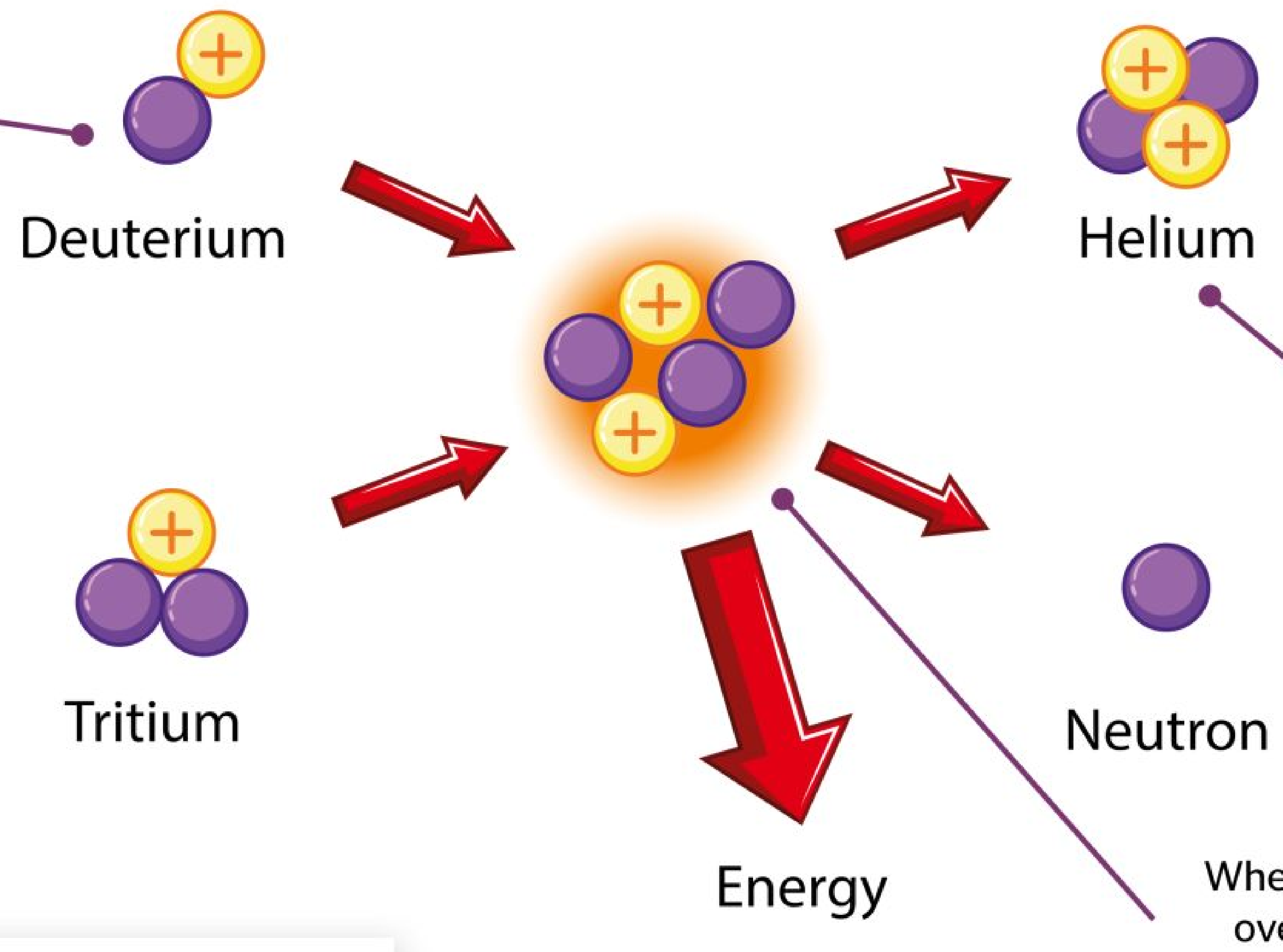
FUSION

Deuterium and tritium

Deuterium nuclei contain one proton (yellow) and one neutron (purple). Tritium nuclei have an extra neutron.

Fusion products

Fusion generates a nucleus of a larger element (helium) and a neutron is emitted. Energy is released in the process.



Fusion reaction

When brought together at over 100 million degrees Celsius, the deuterium and tritium nuclei undergo a nuclear fusion reaction.

Binding energy

The binding energy is the energy required to separate a pair of nucleons (ie protons and neutrons). It varies with the number of nucleons in the nucleus (the atomic weight), rising to a maximum between about 50 and 70 nucleons. Because both the large fissile (capable of fission) nuclei and the small fusile (capable of fusion) nuclei have a smaller binding energy than that of the nuclei they become during fission or fusion, energy is released in the reaction.

The shape of the graph also explains why more energy is available from fusion than fission. Due to the particularly steep curve for small numbers of nucleons, there is a large difference between the binding energy of fusile nuclei (2H and 3H) and that of the result of the fusion (4He).

Energy release

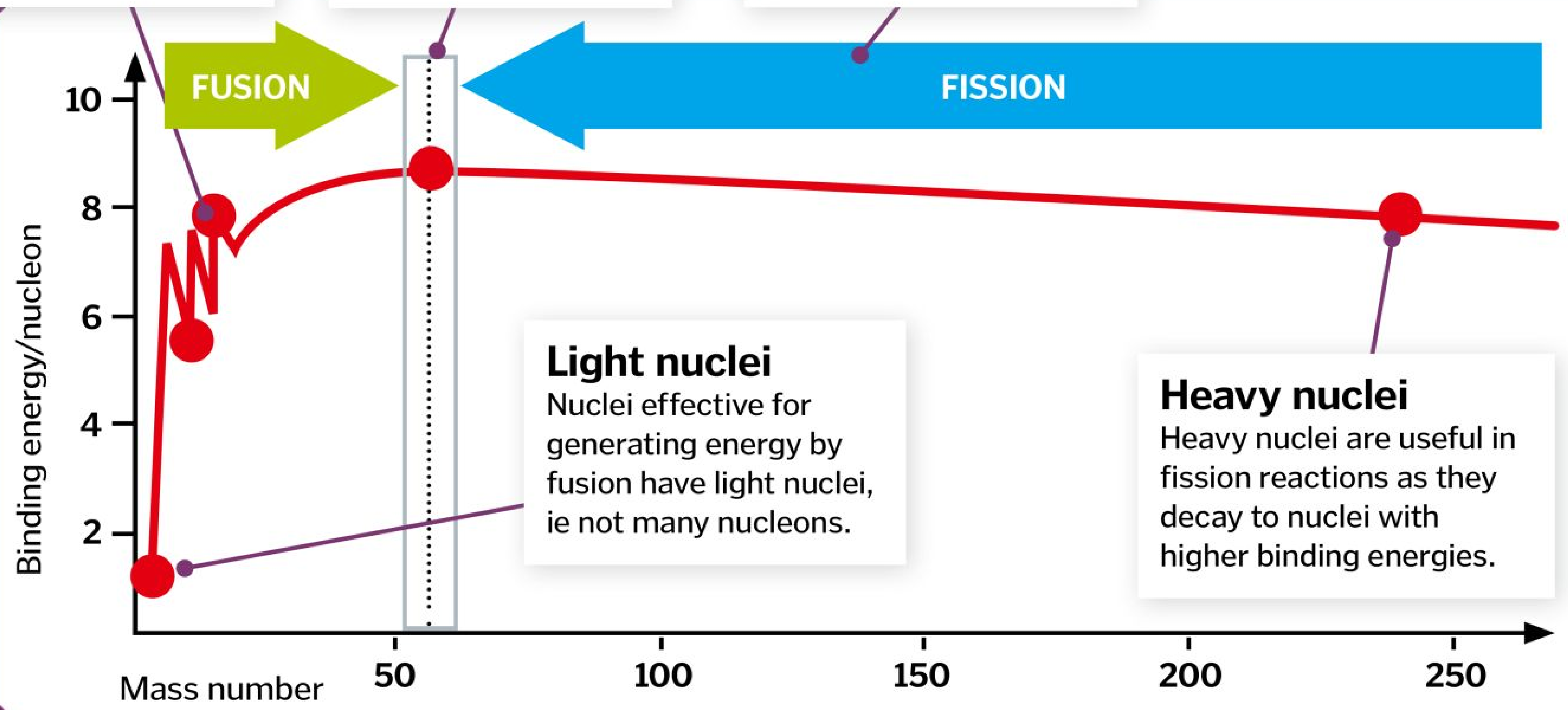
Fusion causes light nuclei to become nuclei with a higher binding energy, releasing energy.

Stable region

Iron and the elements close to it in terms of atomic mass have tightly-bound nuclei.

Fission or fusion?

Lighter elements release energy by fusion, while heavier elements release it by fission.



Light nuclei

Nuclei effective for generating energy by fusion have light nuclei, ie not many nucleons.

Heavy nuclei

Heavy nuclei are useful in fission reactions as they decay to nuclei with higher binding energies.

© Shutterstock; Nuclear Regulatory Commission; ITER Organization, http://www.iter.org

Scientists first recognised the potential of nuclear energy in the 1930s and, while he was by no means the only researcher of note, Italian physicist Enrico Fermi has been acknowledged as the 'architect of the nuclear age'. In 1939, Fermi took up a position at Columbia University in the US, where he detected the release of energy from nuclear fission and, by 1942, had helped to build the world's first self-sustaining controlled nuclear chain reaction. However, political events were soon to alter the course of research into nuclear technology. With America involved in World War 2, Fermi was enlisted into the Manhattan Project where, together with other eminent scientists, most notably Robert Oppenheimer, he would be instrumental in the development of the nuclear bomb.

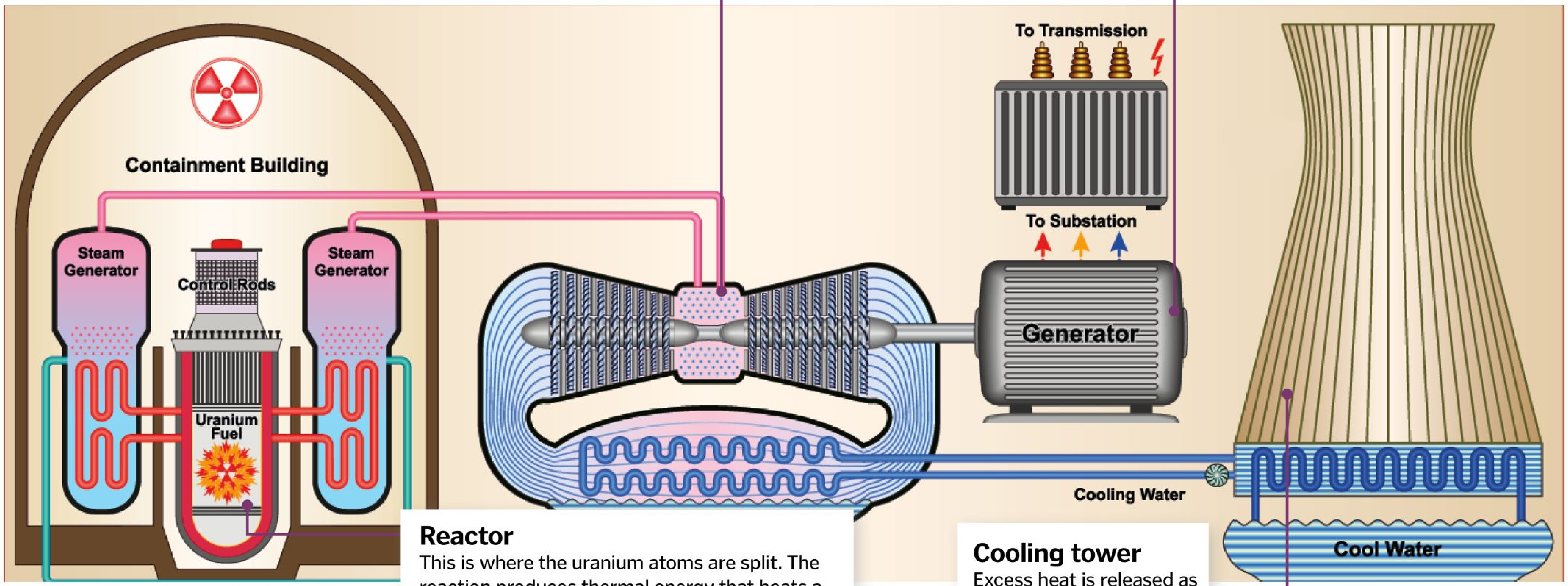
Following the end of hostilities, attention returned to nuclear fission as an energy source for peaceful applications. The first commercial nuclear power station, Calder Hall in the UK, opened in 1956, generating 50 megawatts. Within just a few years, nuclear power plants were also operating in the US, Canada, France and the USSR. Today, there are about 450 operational stations in 30 countries.

Although the atom was once thought to be indivisible, nuclear fission involves just that, splitting an atom of a large atomic weight into two atoms of lower atomic weight. The element of choice, as used in nuclear power plants, is uranium – but not just any uranium. An element is defined by the number of protons in its nucleus and for uranium this is 92, a number known as its atomic number.

Sizewell B is the only nuclear power plant in the UK to use a pressurised water reactor

How a nuclear power plant works

How do we turn nuclear energy into electricity?

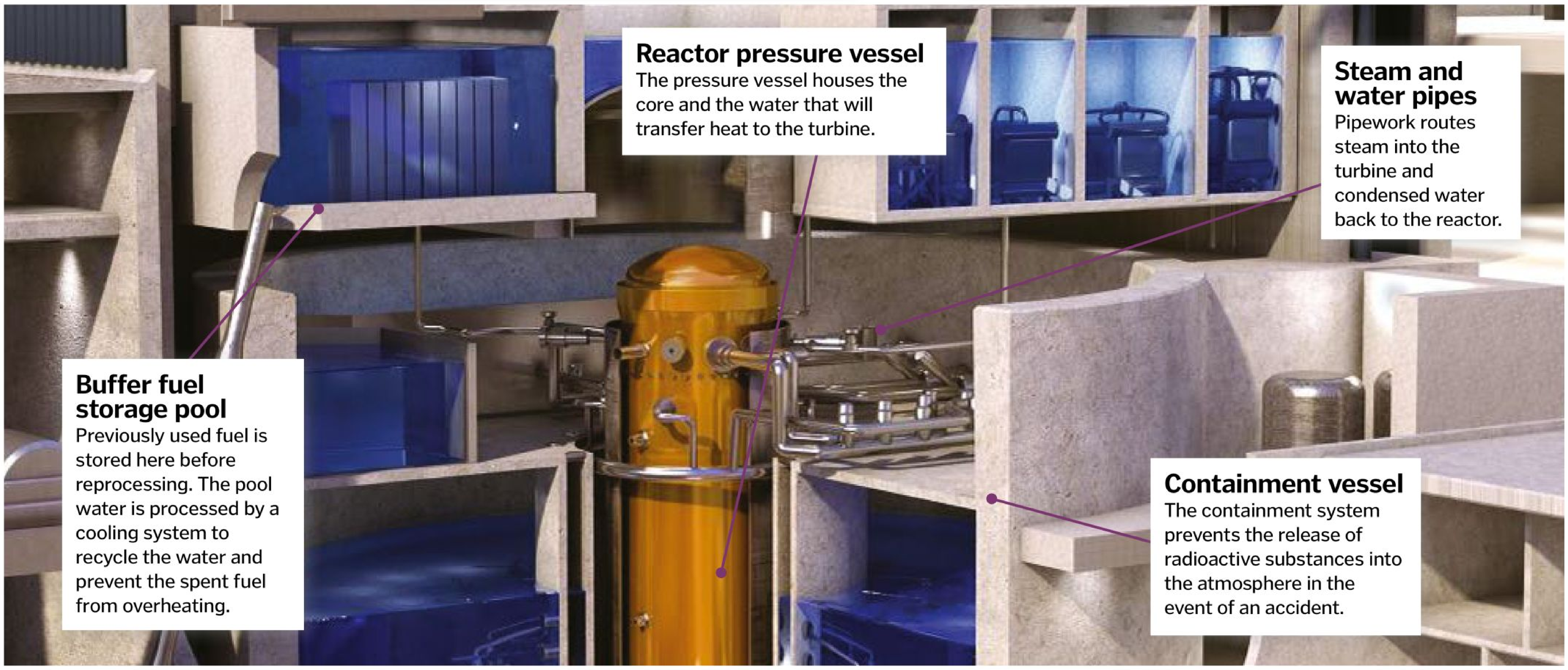


Turbine
The steam produced by the heat of the reaction spins a turbine.

Electricity
Generators transform the kinetic energy of the spinning turbines into electricity.

Reactor
This is where the uranium atoms are split. The reaction produces thermal energy that heats a coolant (typically water) in the steam generator.

Cooling tower
Excess heat is released as clean water vapour.



Reactor pressure vessel
The pressure vessel houses the core and the water that will transfer heat to the turbine.

Steam and water pipes
Pipework routes steam into the turbine and condensed water back to the reactor.

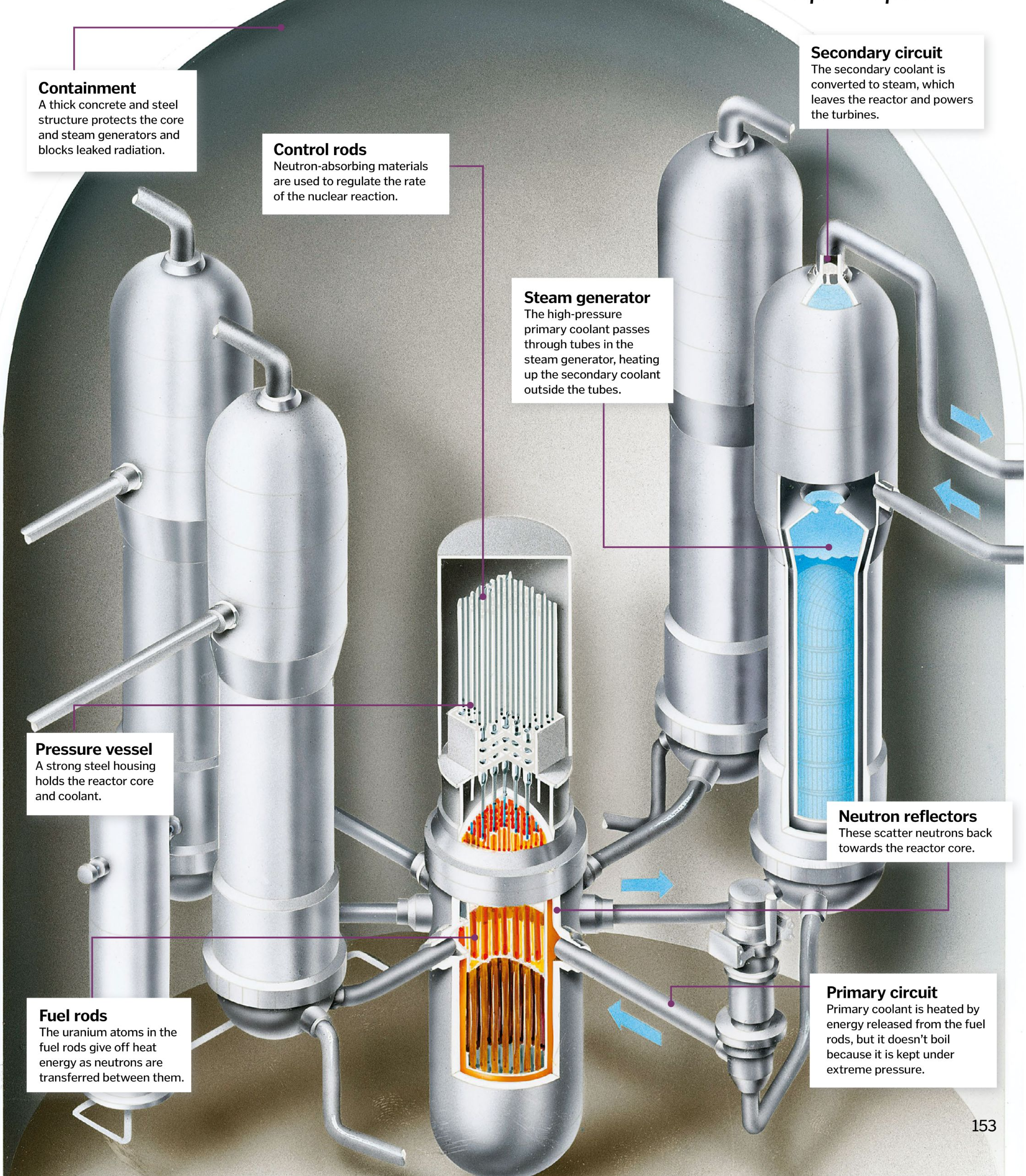
Buffer fuel storage pool
Previously used fuel is stored here before reprocessing. The pool water is processed by a cooling system to recycle the water and prevent the spent fuel from overheating.

Containment vessel
The containment system prevents the release of radioactive substances into the atmosphere in the event of an accident.

How the reactor works

Nuclear cores are carefully designed to ensure they are safe and efficient

> *"Nuclear energy is used to power all manner of things, from submarines to space probes"*



Containment
A thick concrete and steel structure protects the core and steam generators and blocks leaked radiation.

Control rods
Neutron-absorbing materials are used to regulate the rate of the nuclear reaction.

Secondary circuit
The secondary coolant is converted to steam, which leaves the reactor and powers the turbines.

Steam generator
The high-pressure primary coolant passes through tubes in the steam generator, heating up the secondary coolant outside the tubes.

Pressure vessel
A strong steel housing holds the reactor core and coolant.

Neutron reflectors
These scatter neutrons back towards the reactor core.

Fuel rods
The uranium atoms in the fuel rods give off heat energy as neutrons are transferred between them.

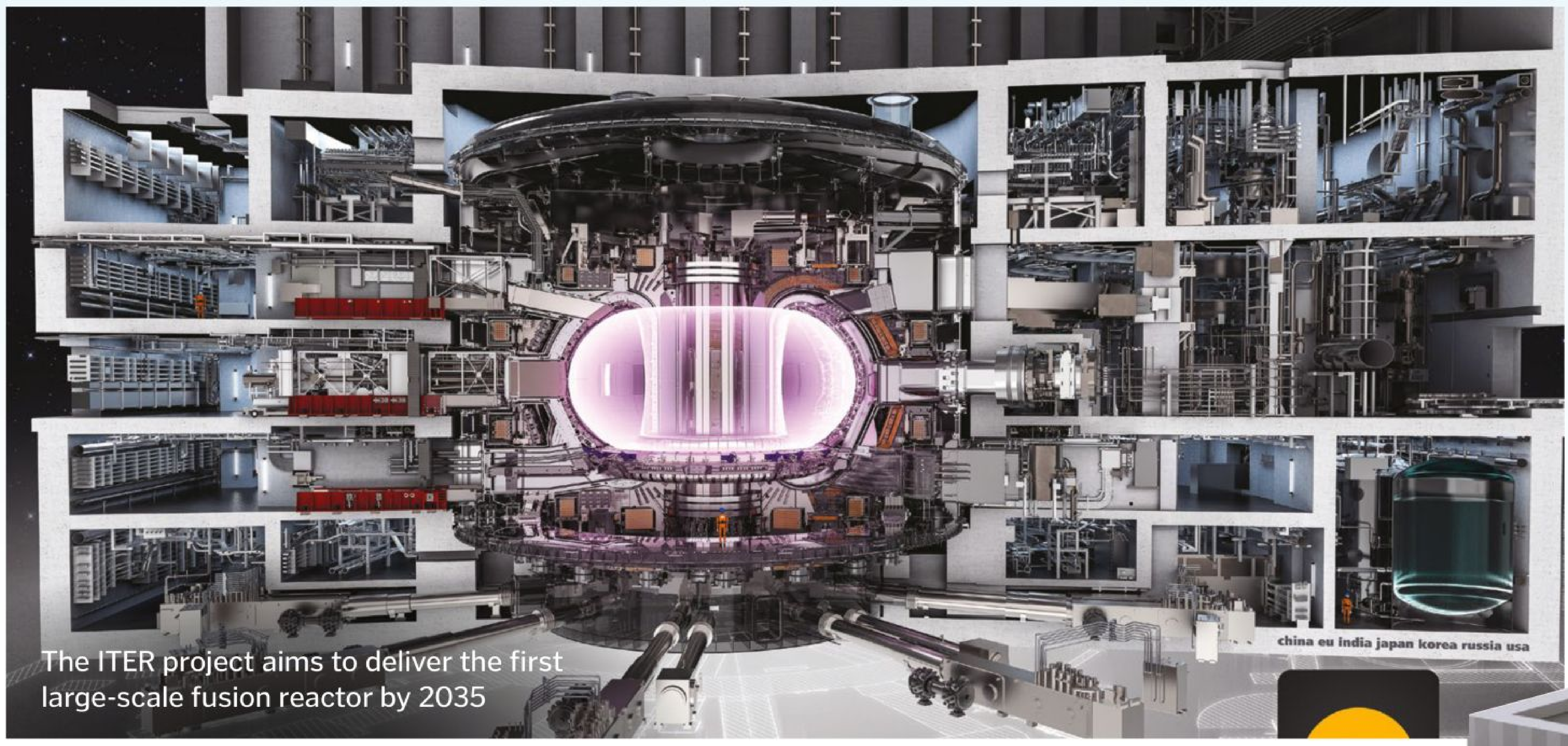
Primary circuit
Primary coolant is heated by energy released from the fuel rods, but it doesn't boil because it is kept under extreme pressure.

However, elements can exist in several forms, known as isotopes, which differ in the number of neutrons in their nucleus. Uranium isotopes include uranium-235 (otherwise denoted as 235U) and uranium-238 (238U), where the number is the atomic weight, which is the sum of the number of protons and neutrons. Naturally occurring uranium is about 99.27 per cent uranium-238 and only 0.7 per cent uranium-235 – not particularly useful for energy generation because uranium-235 is the isotope that can undergo fission (uranium-238 cannot sustain a fission chain reaction). To be useful as a fuel, therefore, the concentration of the fissile uranium-235 has to be increased in a process called enrichment. Because the chemical properties of the two main isotopes of uranium are very similar, enrichment is a lengthy process in which the concentration of uranium-235 is increased in steps. The enriched uranium used for power generation has about three to five per cent uranium-235.

Fission of uranium-235 occurs when neutrons are fired at it. The neutron is initially captured by the uranium-235, but this makes it highly unstable, causing it to split into two other elements, releasing energy in the process. Fission of uranium-235 can give rise to a whole range of by-products, although isotopes of barium and krypton are two of the most common. Most of these by-products are highly radioactive in themselves, so they, in turn, also decay. Crucially, though, the fission reaction also releases two or three neutrons, which are then free to collide with other uranium-235 atoms, and so cause them to undergo nuclear fission. This gives rise to a chain reaction, which means that the fusion reaction, once initiated, is self-sustaining. In fact, in a nuclear reactor, unless controlled, this process will result in the release of energy much too quickly, with disastrous consequences, as evidenced by the destruction of a reactor at the Chernobyl nuclear power station in 1986.

The solution is to use a material capable of neutron capture without itself undergoing fission, most commonly boron. These materials are fashioned into so-called control rods and housed in the reactor core. By raising and lowering the control rods, the neutron flux can be controlled to allow the fission reaction to take place while preventing a runaway situation, an eventuality called criticality. They also allow an emergency shut down of the reactor.

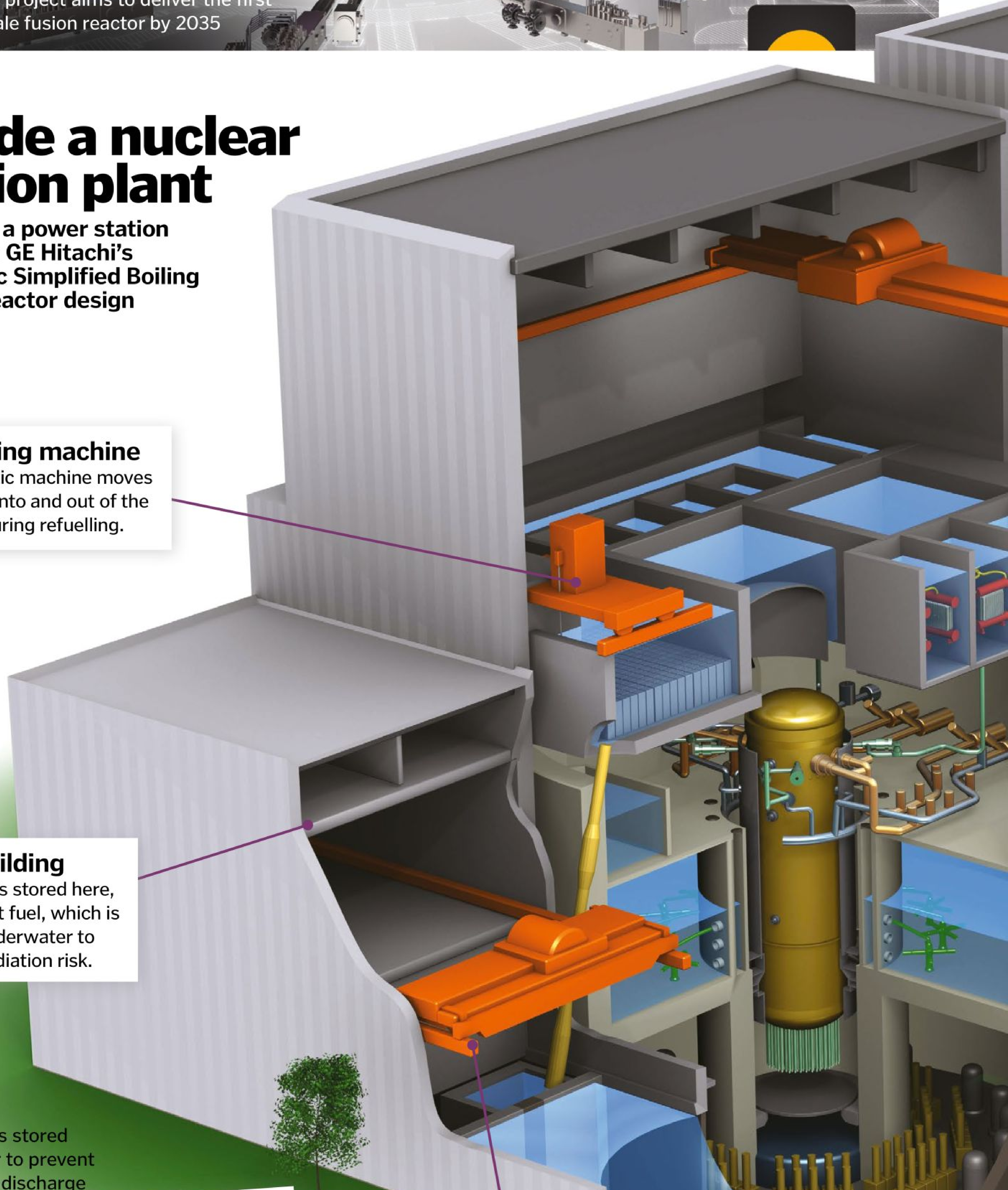
Discussion of nuclear power stations inevitably leads to talk of the various types of reactor, with names such as the pressurised water reactor, the boiling water reactor and the Magnox or gas-cooled reactor bandied around. At the highest level, though, all nuclear power



The ITER project aims to deliver the first large-scale fusion reactor by 2035

Inside a nuclear fission plant

A tour of a power station based on GE Hitachi's Economic Simplified Boiling Water Reactor design

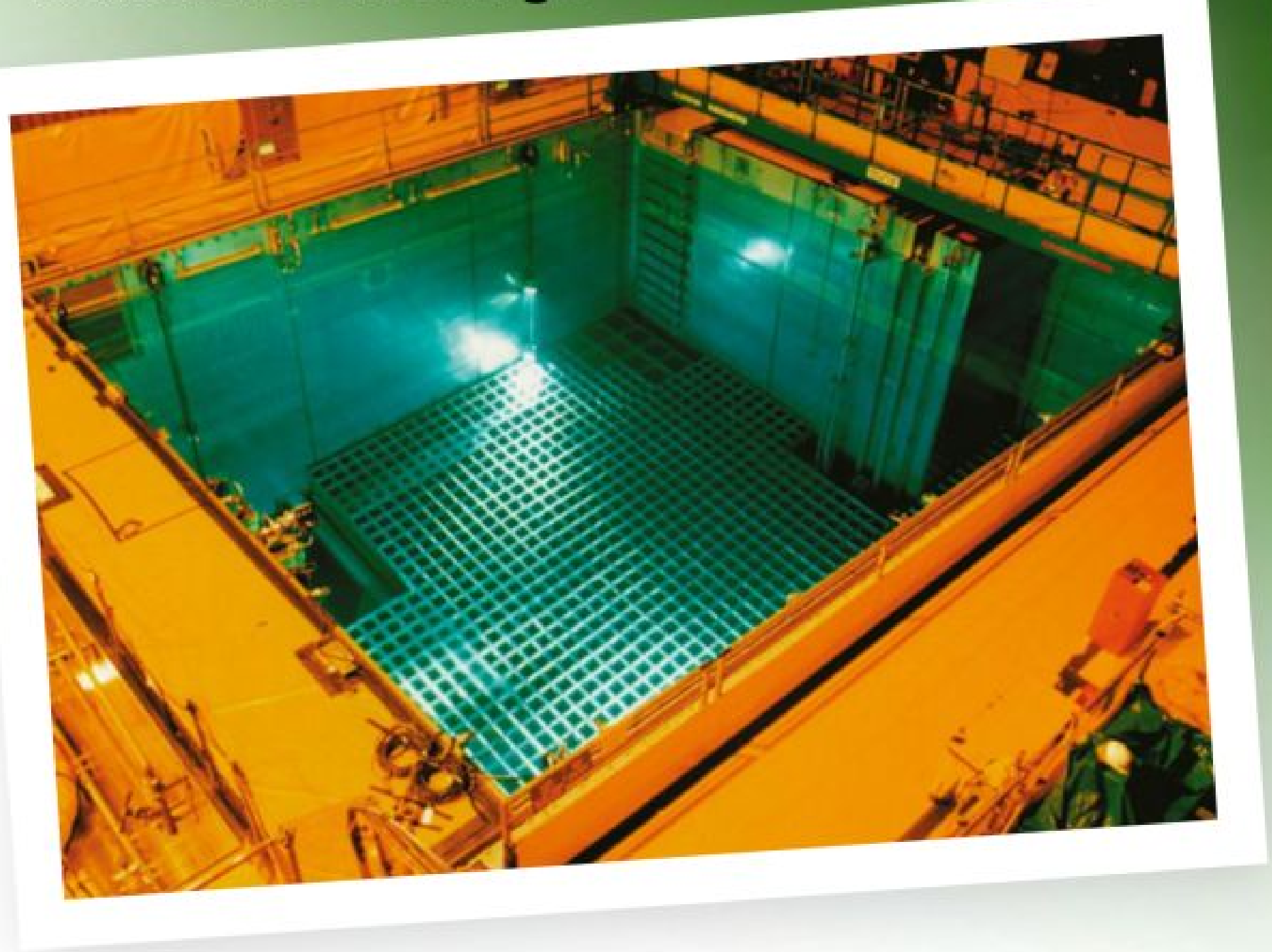


Refuelling machine
This robotic machine moves fuel rods into and out of the reactor during refuelling.

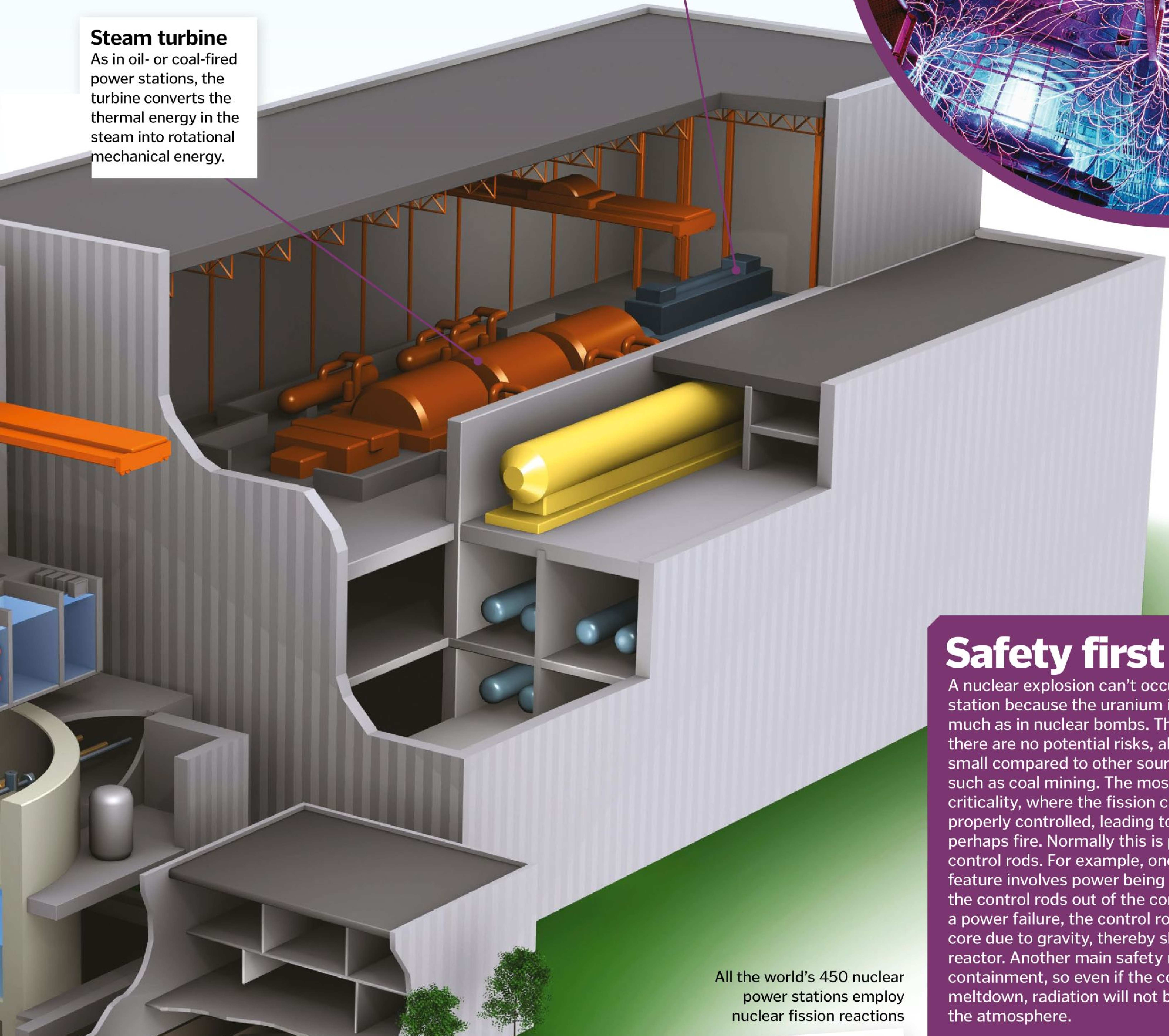
Fuel building
New fuel is stored here, as is spent fuel, which is stored underwater to reduce radiation risk.

Inclined fuel transfer system
The inclined fuel transfer system transfers new and used fuel between the fuel building and the containment vessel.

Spent fuel is stored underwater to prevent radioactive discharge



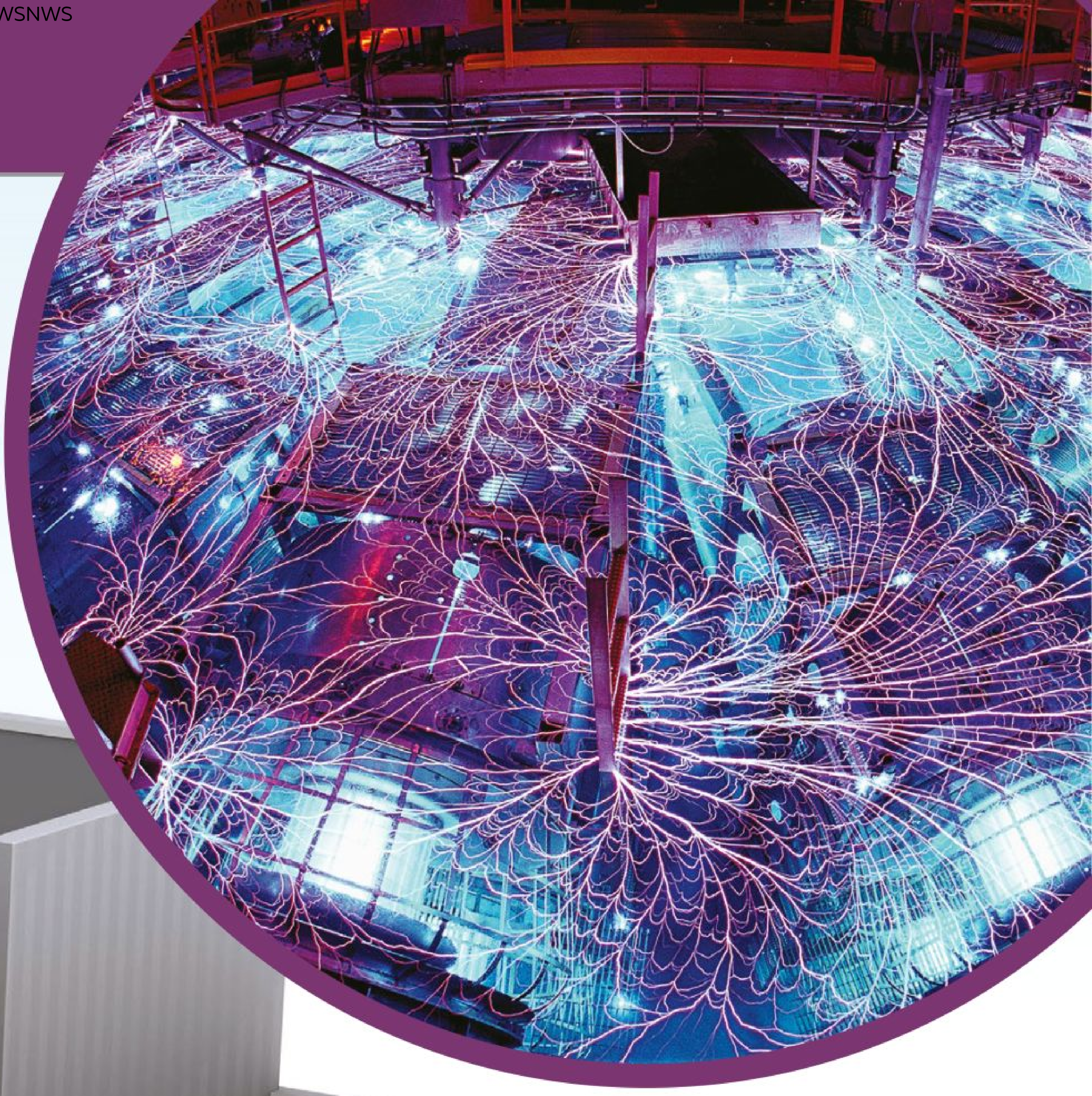
> *"The difference between reactor types relates to the way the heat is extracted from the core"*



Generator
Sharing a drive shaft with the turbine, the generator converts the mechanical energy into electrical energy.

Steam turbine
As in oil- or coal-fired power stations, the turbine converts the thermal energy in the steam into rotational mechanical energy.

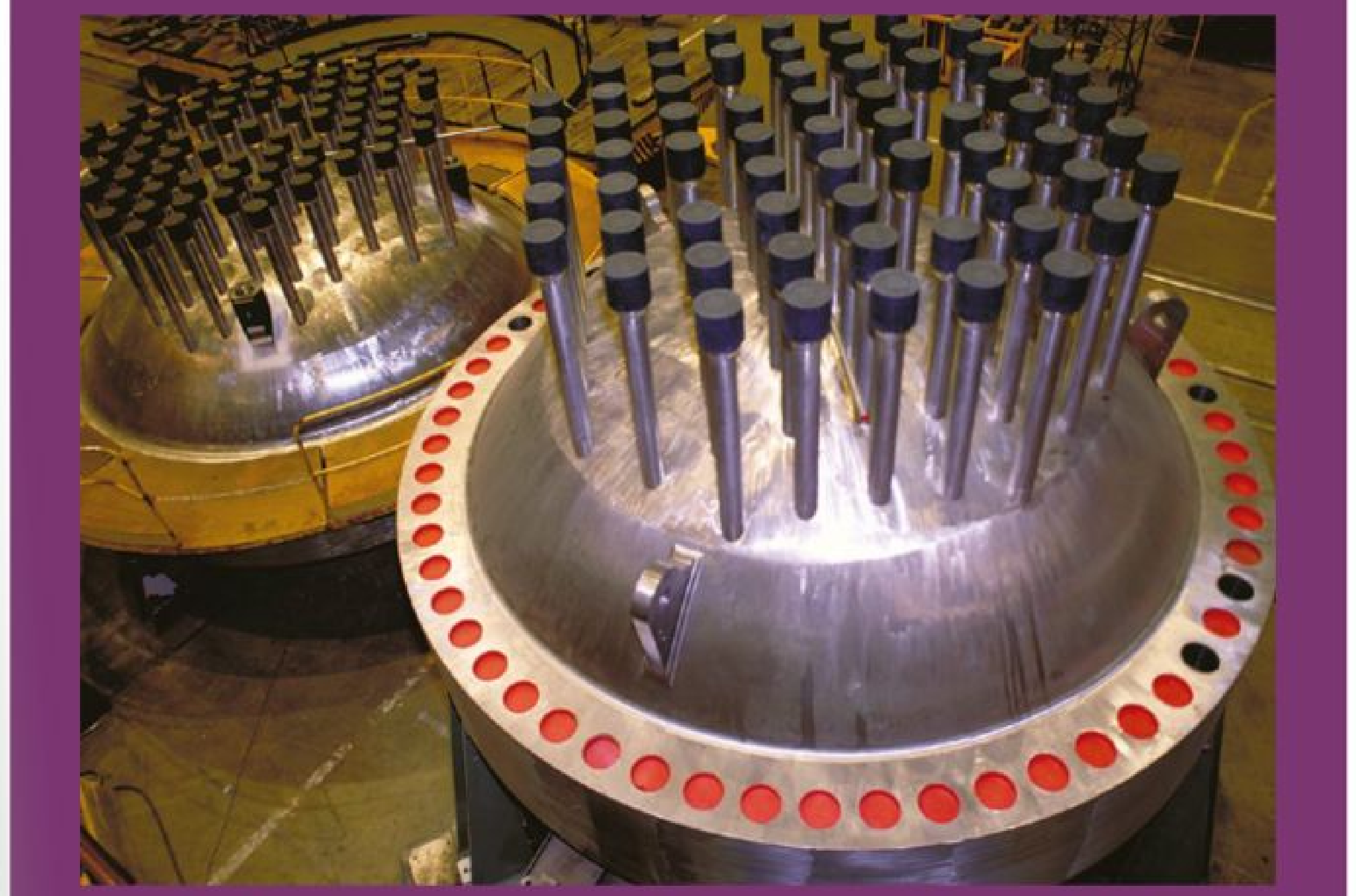
Control room
Although automated systems play a role, operators in the control room can monitor and control power station operations.



Sandia Laboratory's Z Machine is used for researching high temperatures and pressures as needed for nuclear fusion

Safety first

A nuclear explosion can't occur in a power station because the uranium isn't enriched as much as in nuclear bombs. This isn't to say there are no potential risks, although they're small compared to other sources of energy, such as coal mining. The most obvious risk is criticality, where the fission chain reaction isn't properly controlled, leading to overheating and perhaps fire. Normally this is prevented using control rods. For example, one clever safety feature involves power being needed to hold the control rods out of the core. In the event of a power failure, the control rods fall into the core due to gravity, thereby shutting down the reactor. Another main safety measure is containment, so even if the core suffers a meltdown, radiation will not be released into the atmosphere.



Control rods are essential in preventing criticality from occurring in a nuclear reactor

All the world's 450 nuclear power stations employ nuclear fission reactions

© NRC; GE; Sandia Labs; Getty

stations work in much the same way. The nuclear fission reaction generates heat, the heat turns water into steam and, from here on, things are the same as in a coal- or oil-fired power station. The steam drives a turbine, which in turn drives a generator that produces electricity.

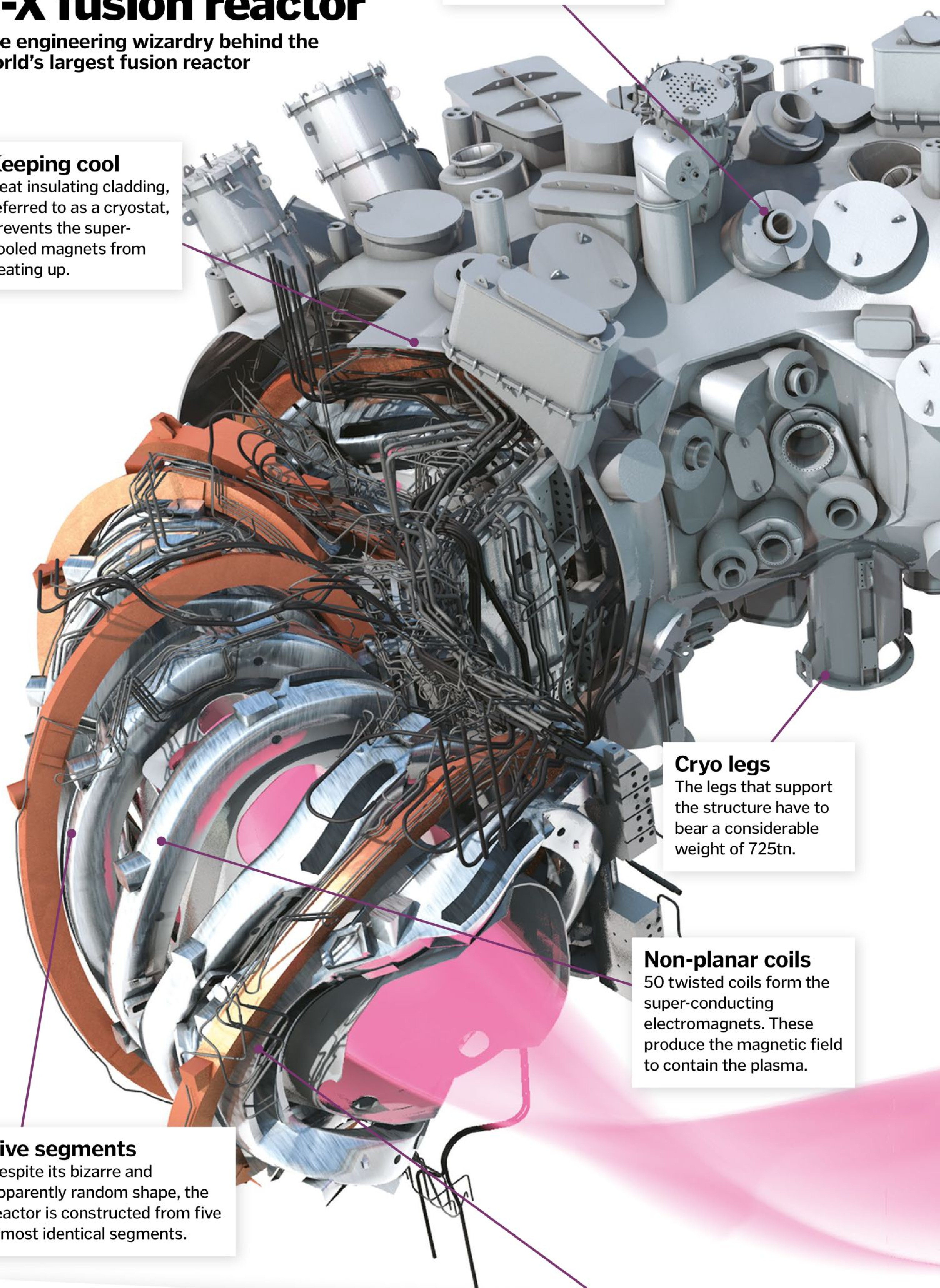
The difference between the various reactor types relates to the way the heat is extracted from the core. In the boiling water reactor, the water that is heated to produce the steam is pumped through the nuclear reactor. In the pressurised water reactor, on the other hand, to prevent contaminated steam entering the turbine, there are two water circuits. The primary water flows through the reactor, which gives up its heat to the secondary water in a heat exchanger, the secondary water turning to steam and driving the turbine. The advanced gas-cooled reactor, as favoured in the UK, is similar except that the primary circuit, which transfers heat from the reactor to the water in the secondary circuit, uses carbon dioxide instead.

So much for the current state of play, but the Holy Grail of nuclear power is fusion rather than fission. As the name suggests, nuclear fusion is the opposite of nuclear fission – two atomic nuclei merging to produce an element with a larger atomic mass. Again this generates energy; the plentiful energy that the Earth receives from the Sun is the result of a massive nuclear fusion reaction. One of the Sun's fusion reactions, and the one that has been the subject of most research, occurs between two isotopes of hydrogen, namely deuterium (hydrogen-2) and tritium (hydrogen-3) to produce helium. Fusion produces much more energy than fission and the by-products are not as radioactive, thereby reducing concerns over nuclear waste, plus the raw materials are potentially plentiful. Yet despite these benefits, there are some serious challenges to be met before fusion can form the basis for power generation. In particular, to initiate and maintain the reaction temperatures of over 100 million degrees Celsius are needed, and to hold the deuterium and tritium atoms together a magnetic field thousands of times that of Earth's own is required.

Burning fossil fuels generates greenhouse gasses, but nuclear fission – while producing about 11 per cent of the world's electricity without producing carbon dioxide – has its critics. While renewables will undoubtedly play an important role in the future, the potential benefits of fusion, should it ever come to fruition, can't be ignored. Currently, a project involving China, the European Union, India, Japan, South Korea, Russia and the United States is causing considerable interest. Called ITER, the aim is to produce the first operating large-scale fusion reactor by 2035, so watch this space.

The Wendelstein 7-X fusion reactor

The engineering wizardry behind the world's largest fusion reactor



Ports
No fewer than 253 ports provide access to the centre of the reactor for monitoring and regulating the reaction process.

Keeping cool
Heat insulating cladding, referred to as a cryostat, prevents the super-cooled magnets from heating up.

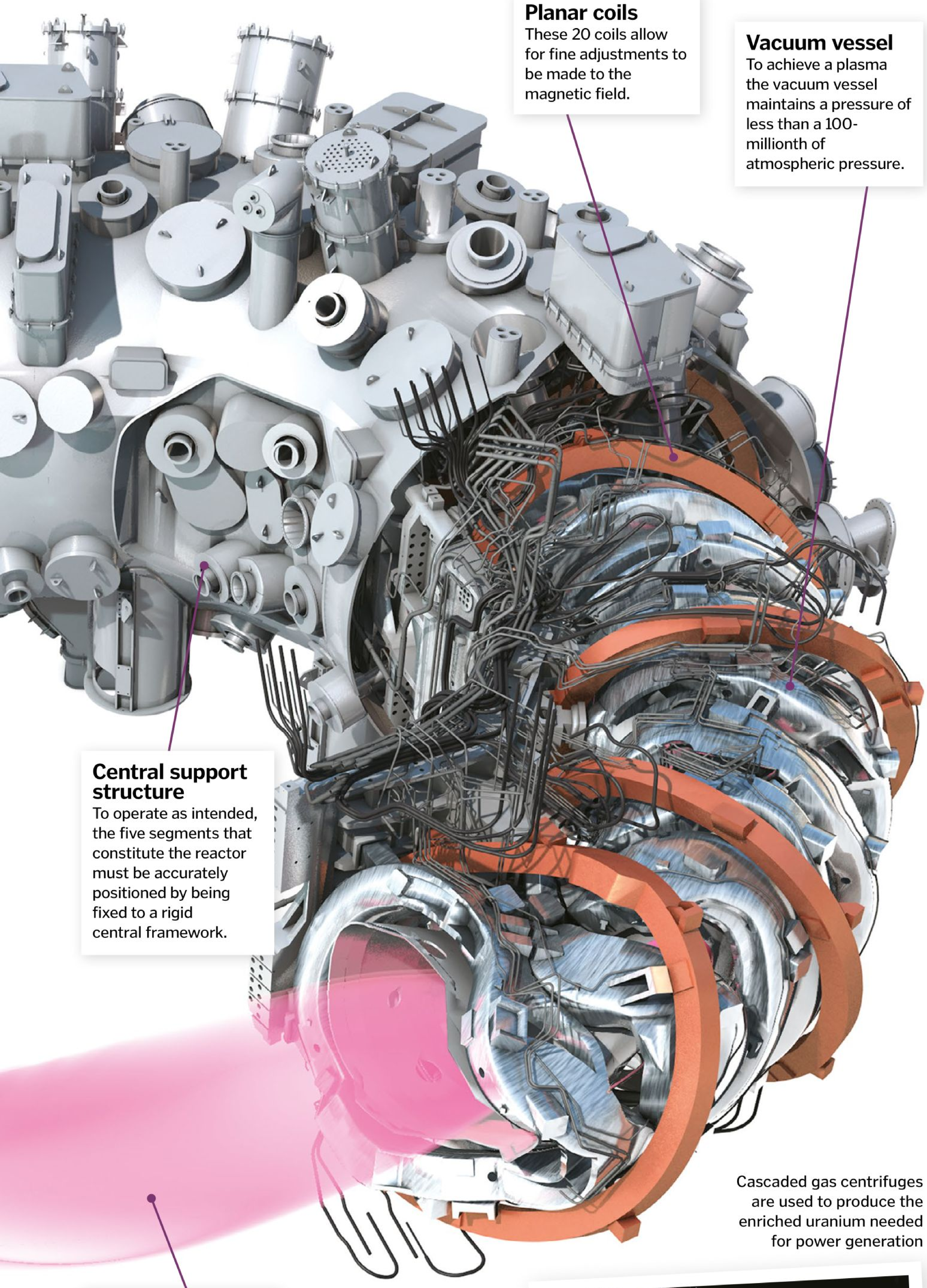
Cryo legs
The legs that support the structure have to bear a considerable weight of 725tn.

Non-planar coils
50 twisted coils form the super-conducting electromagnets. These produce the magnetic field to contain the plasma.

Five segments
Despite its bizarre and apparently random shape, the reactor is constructed from five almost identical segments.

Liquid helium
Liquid helium at -270 degrees Celsius allows the loops that form the magnets to be super-conductive.

The Rossing Mine in Namibia is one of the world's largest producers of uranium



Planar coils
These 20 coils allow for fine adjustments to be made to the magnetic field.

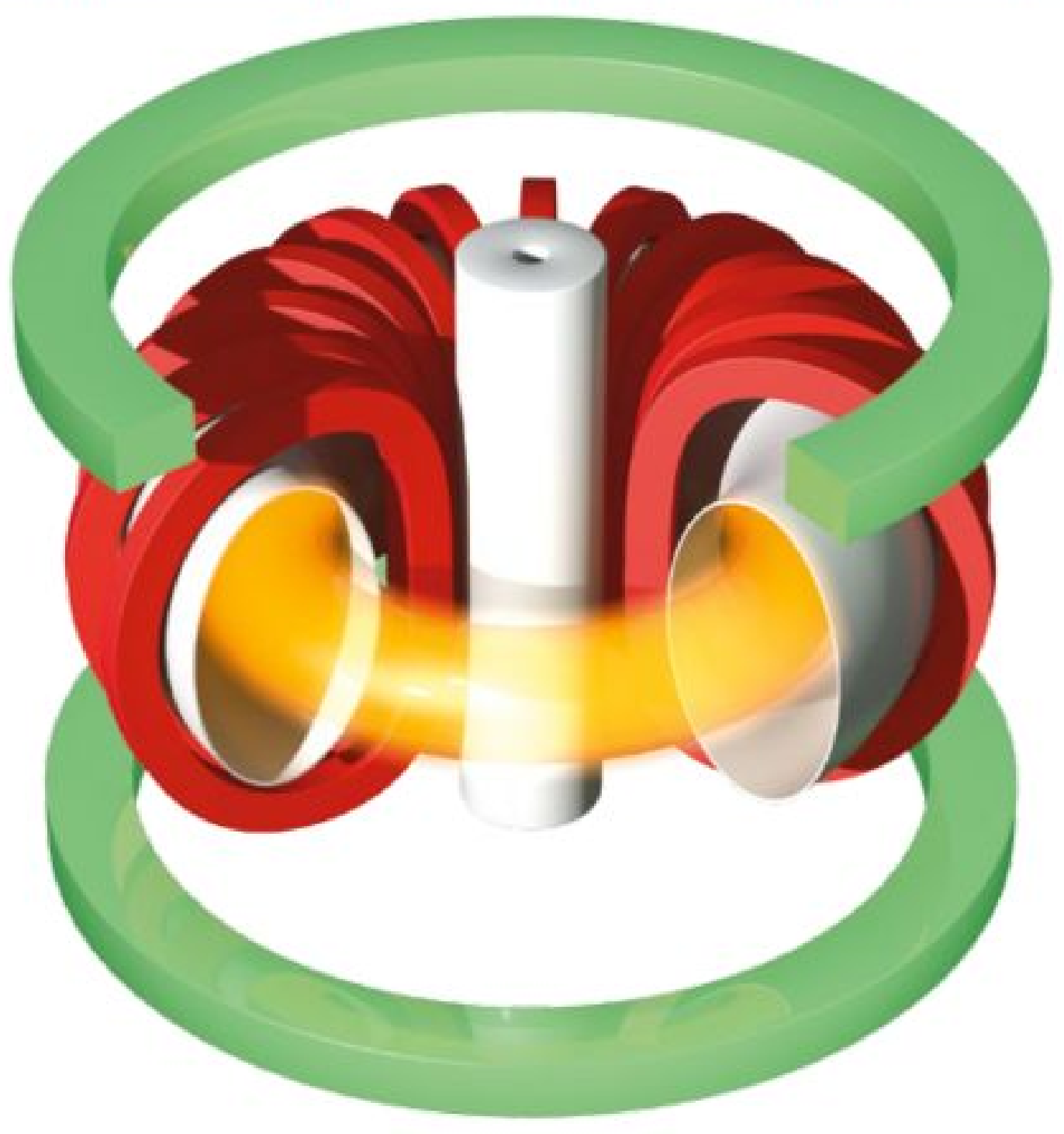
Vacuum vessel
To achieve a plasma the vacuum vessel maintains a pressure of less than a 100-millionth of atmospheric pressure.

Central support structure
To operate as intended, the five segments that constitute the reactor must be accurately positioned by being fixed to a rigid central framework.

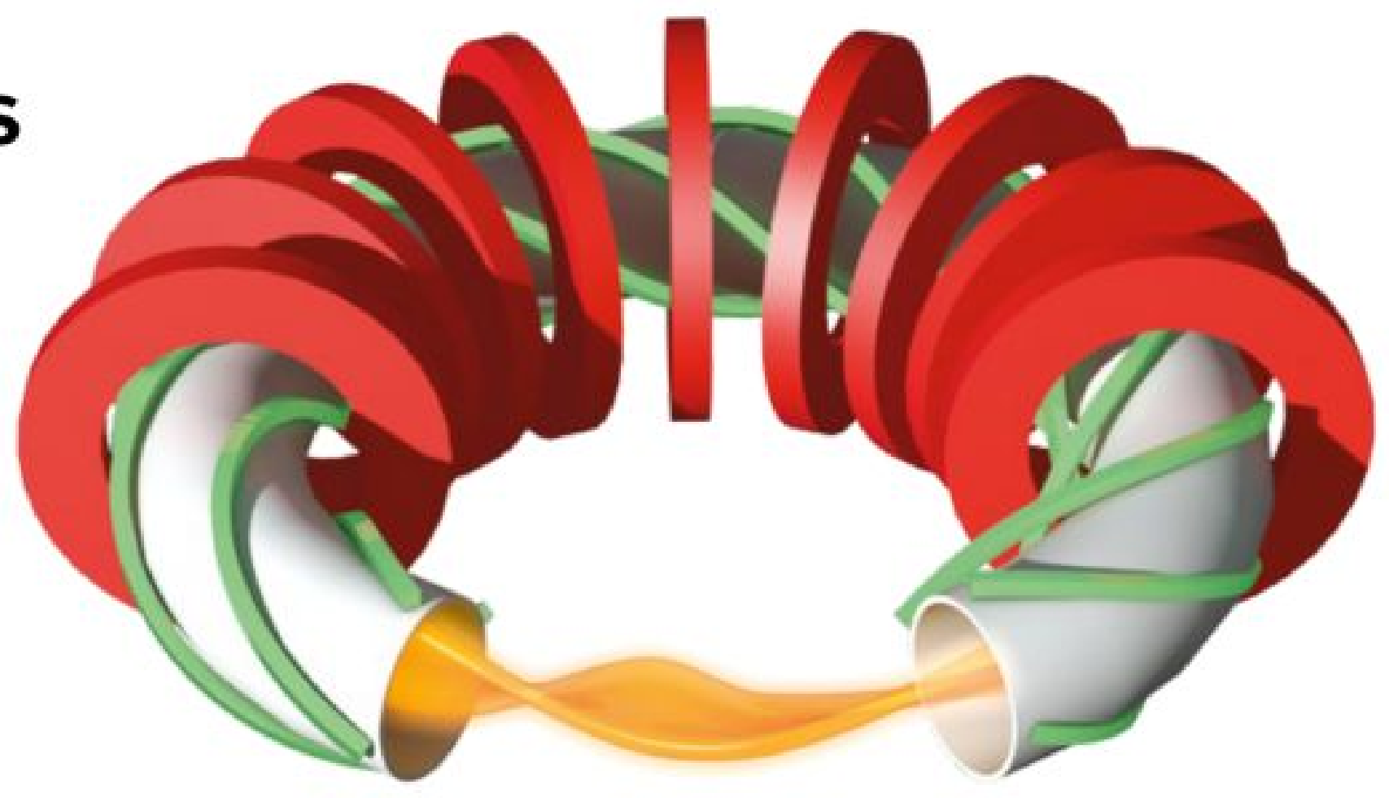
Plasma
The isotopes for fusion are heated to 100 million degrees Celsius, at which temperature they form a plasma.

Comparing alternative fusion reactors

Most fusion reactor designs are toroids with external coils that generate a magnetic field needed to prevent the high temperature plasma from touching the reactor walls. But the magnetic field must have a twist.



Tokamaks
In tokamak reactors, a current flows through the plasma to create the twist.



Stellarators
In stellarator reactors, the whole machine is twisted to achieve a twist in the field.

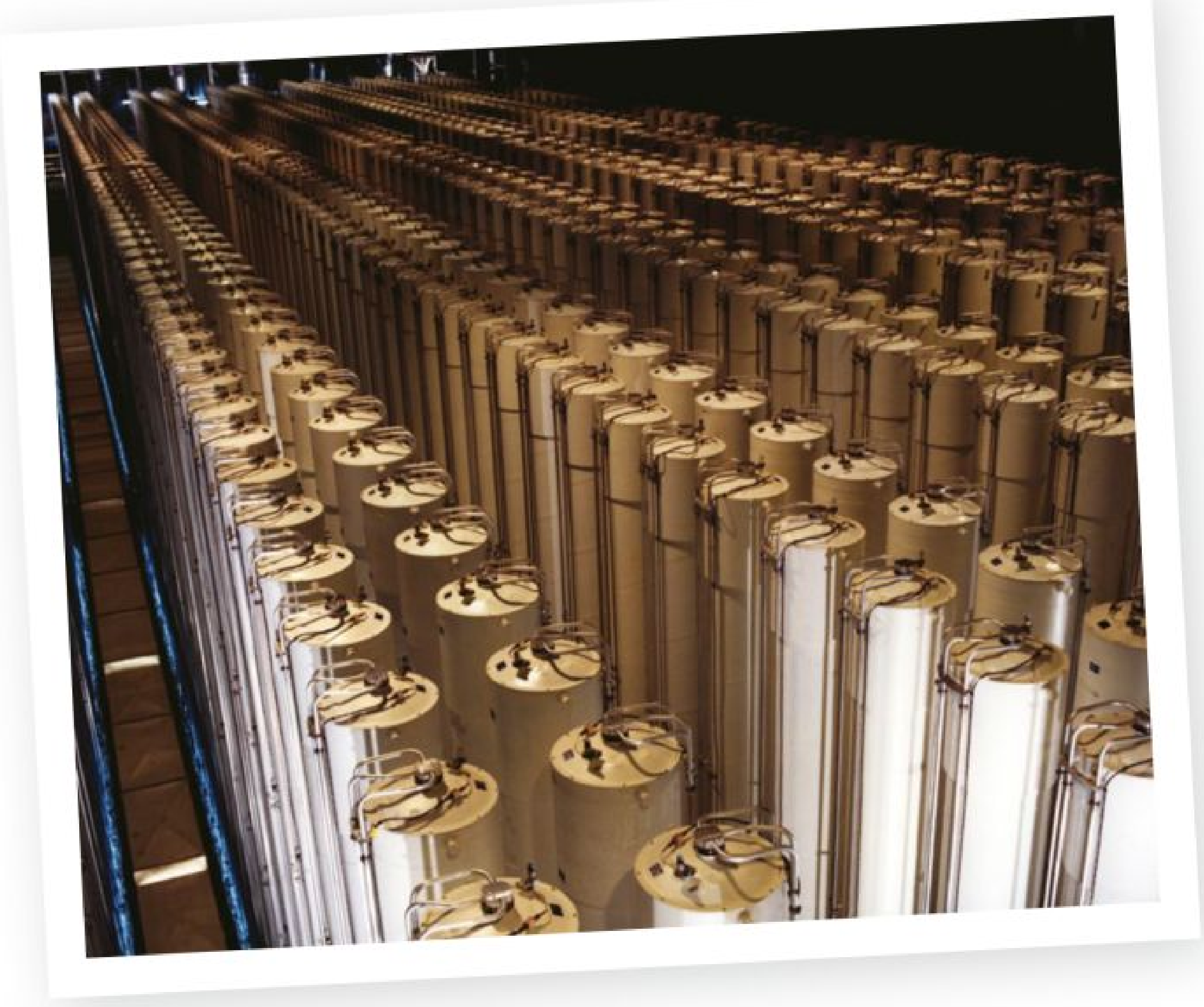
The challenge of fusion

Research into nuclear fusion started decades ago and, for most of that time, commercial applications were thought to be 30 or 40 years away. So why are we getting no closer to a nuclear fusion power station? What's the challenge that's holding it at bay?

Unfortunately, there's no one single challenge but many. One of the most significant is that the necessary temperature is so high that large amounts of energy are needed. For many years experimental fusion reactors used more energy than they generated. A breakthrough came in 2014 at the Lawrence Livermore National Laboratory in the US, when a reactor generated 1.7 times more energy than it consumed. But the reactor was a small-scale device and the challenges are compounded as the technology is scaled up.

It's interesting to note that an aim of the ITER fusion reactor, scheduled for 2035, is to generate 500 megawatts but only use 50.

Lawrence Livermore's National Ignition Facility conducts fusion experiments using ultra-powerful lasers to heat and compress hydrogen fuel

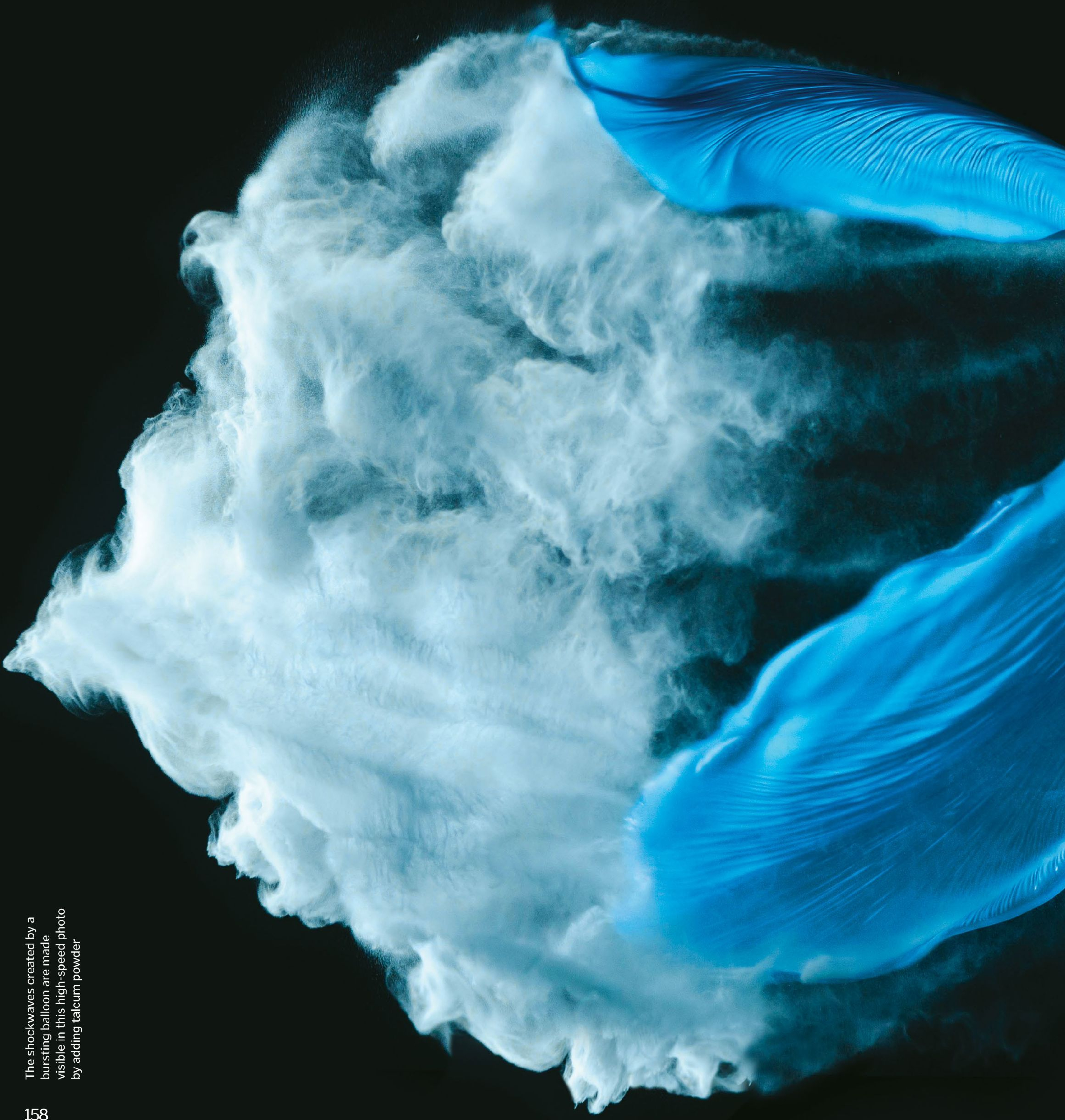


Cascaded gas centrifuges are used to produce the enriched uranium needed for power generation

> *"The Holy Grail of nuclear power is fusion rather than fission"*

© Max-Planck Institute for Plasma Physics; Lawrence Livermore National Laboratory, Damien Jemison; Illustrations by Adrian Mann; USDA; Conleth Brady, IAEA

> *"The tension rapidly transforms this tiny hole into a big tear, ripping the balloon apart with an almighty bang"*



The shockwaves created by a bursting balloon are made visible in this high-speed photo by adding talcum powder

Balloon-popping science

Find out why the properties of latex give bursting balloons their bang

Balloons are made of latex, a special type of polymer called an elastomer. If you were to look at latex under a powerful microscope you would see a tangle of long molecules resembling a plate of cooked spaghetti. Each molecule is linked to its neighbours by bonds called cross-links, forming a dense network. When pulled apart, these tangled molecules straighten out, but as soon as the tension is released they snap back to their original shape, lending latex its stretchy quality.

Inflate a balloon and the latex molecules stretch out, putting the balloon's skin under a large amount of tension. If you then jab the balloon with a needle, you create a tiny fault in the latex. The existing tension rapidly transforms this tiny hole into a big tear, ripping the balloon apart with an almighty bang.

Don't feel embarrassed if popping balloons make you jump – their deafening noise is caused by nothing less than a sonic boom. As the balloon tears, the resulting pieces of latex contract at great speed. The ends of each piece move so fast that they break the speed of sound in latex, sending a shock wave travelling through the material.

Sharp objects aside, any process that creates a weak point somewhere on the balloon makes it liable to pop, from a naked flame to a tiny spark caused by static electricity discharging. Latex also becomes weaker and stiffer over time, allowing faults to develop gradually. This explains why balloons sometimes seem to mysteriously burst of their own accord.

No bang theory

It might seem illogical but there is a way to pierce a balloon without it popping – discover how in this step-by-step...

1. Inflate the balloon

For this trick, use a good-quality, medium-sized balloon. Take a deep breath and inflate the balloon to full size – stretching the latex a little beforehand makes this easier. Then let out about a third of the air and tie a knot.

2. Prepare a skewer

Take a wooden skewer, making sure to pick a sharp one with no splinters which could tear the balloon. Dip the tip of the skewer in vegetable oil, which will act as a lubricant to reduce friction and help the point glide through the balloon's skin.

3. Pierce the balloon

Start at the bottom (beside the knot) as this is where the balloon's polymer molecules are stretched the least. Carefully push the skewer into the balloon where the rubber looks darkest. Gentle pressure will help, but don't jab yourself!

4. Out the other side

Gently push the skewer through the balloon, guiding it toward the opposite end. The latex here is also under less tension than elsewhere, so it can be pierced without bursting the balloon. Push the skewer until it emerges through the skin again.

5. Take a bow

Job done – although you should expect the trick to take a few attempts before you get it right. You can now remove the skewer from the balloon if you wish – it still won't pop at this stage but the air inside the balloon will leak out fairly fast.

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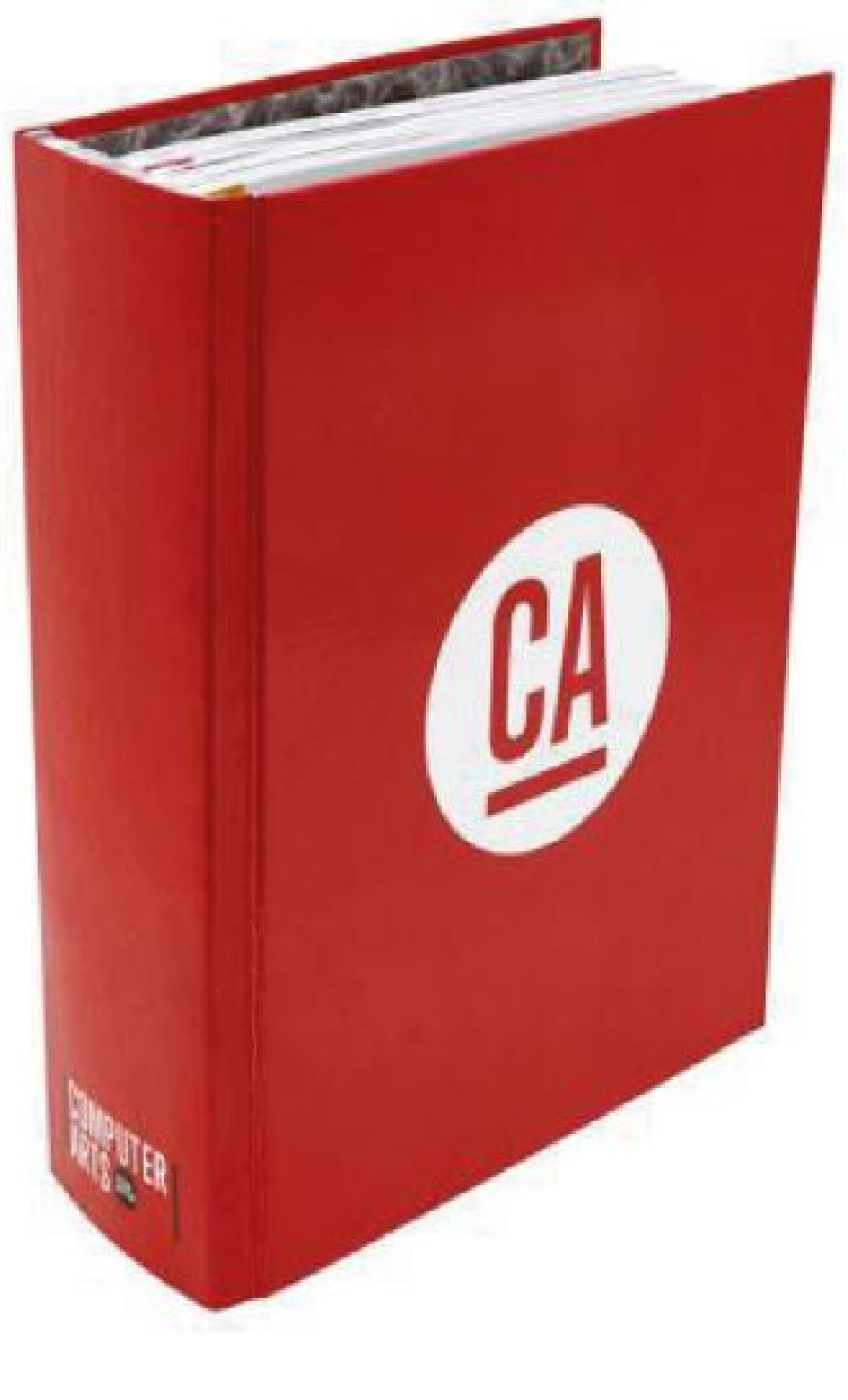

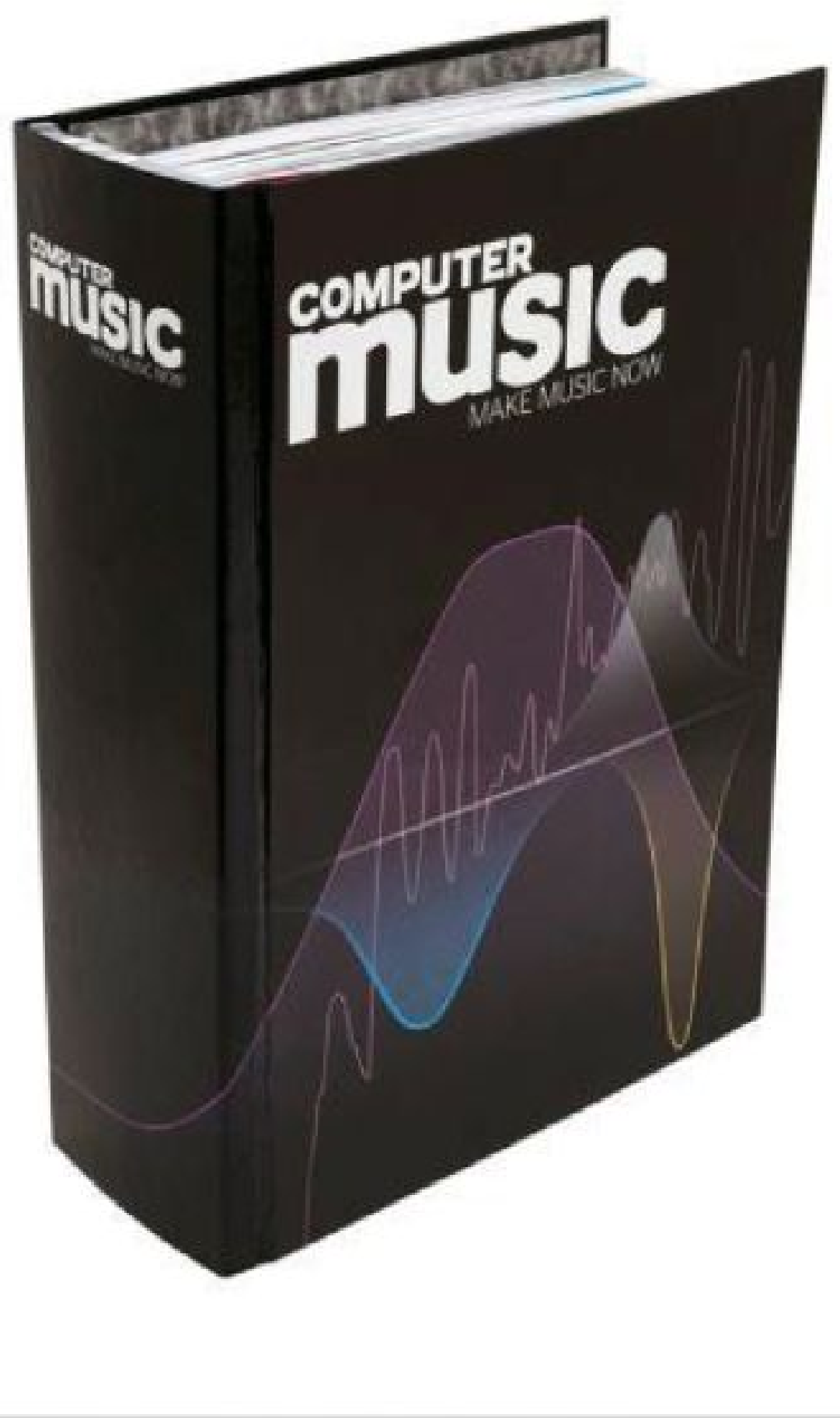

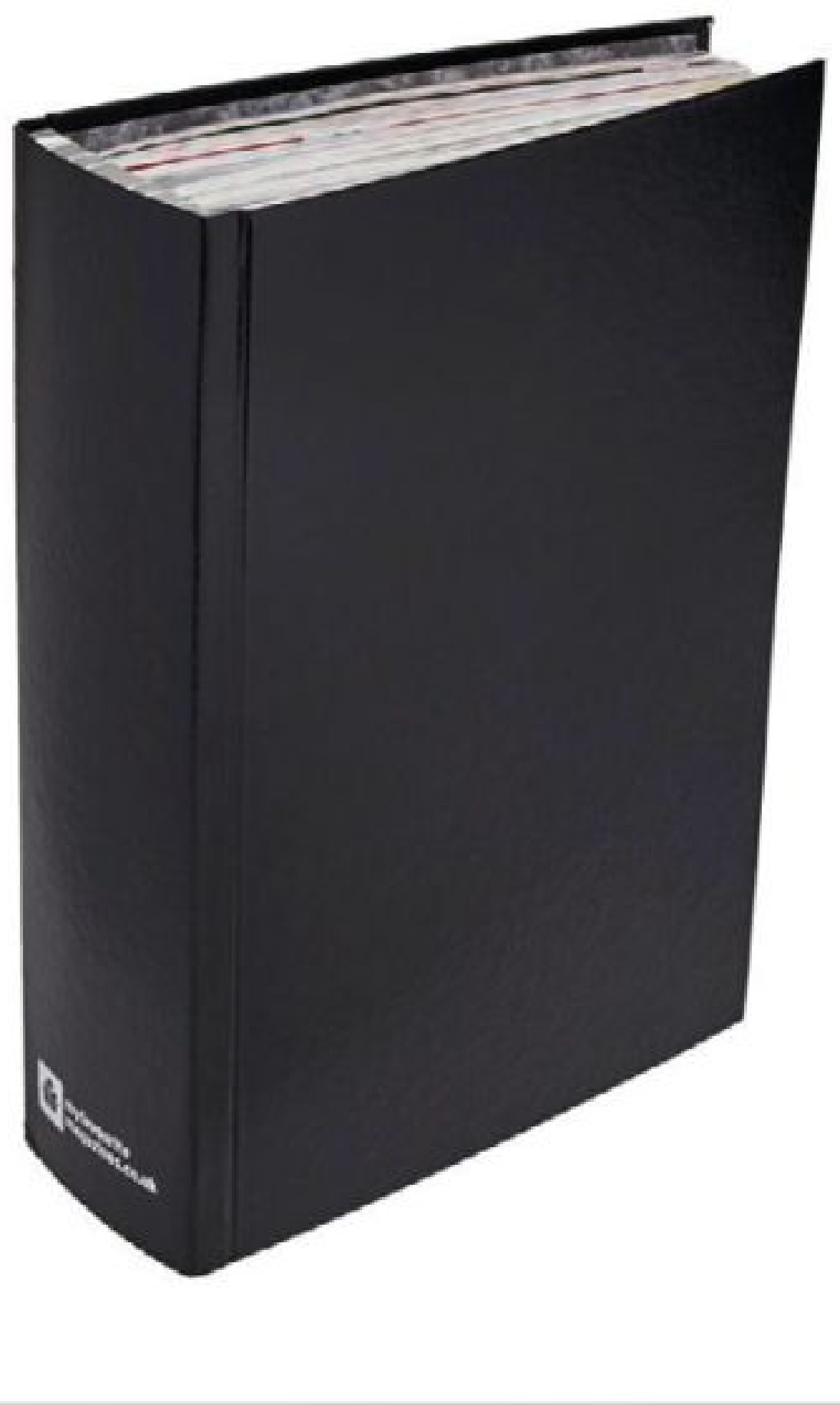

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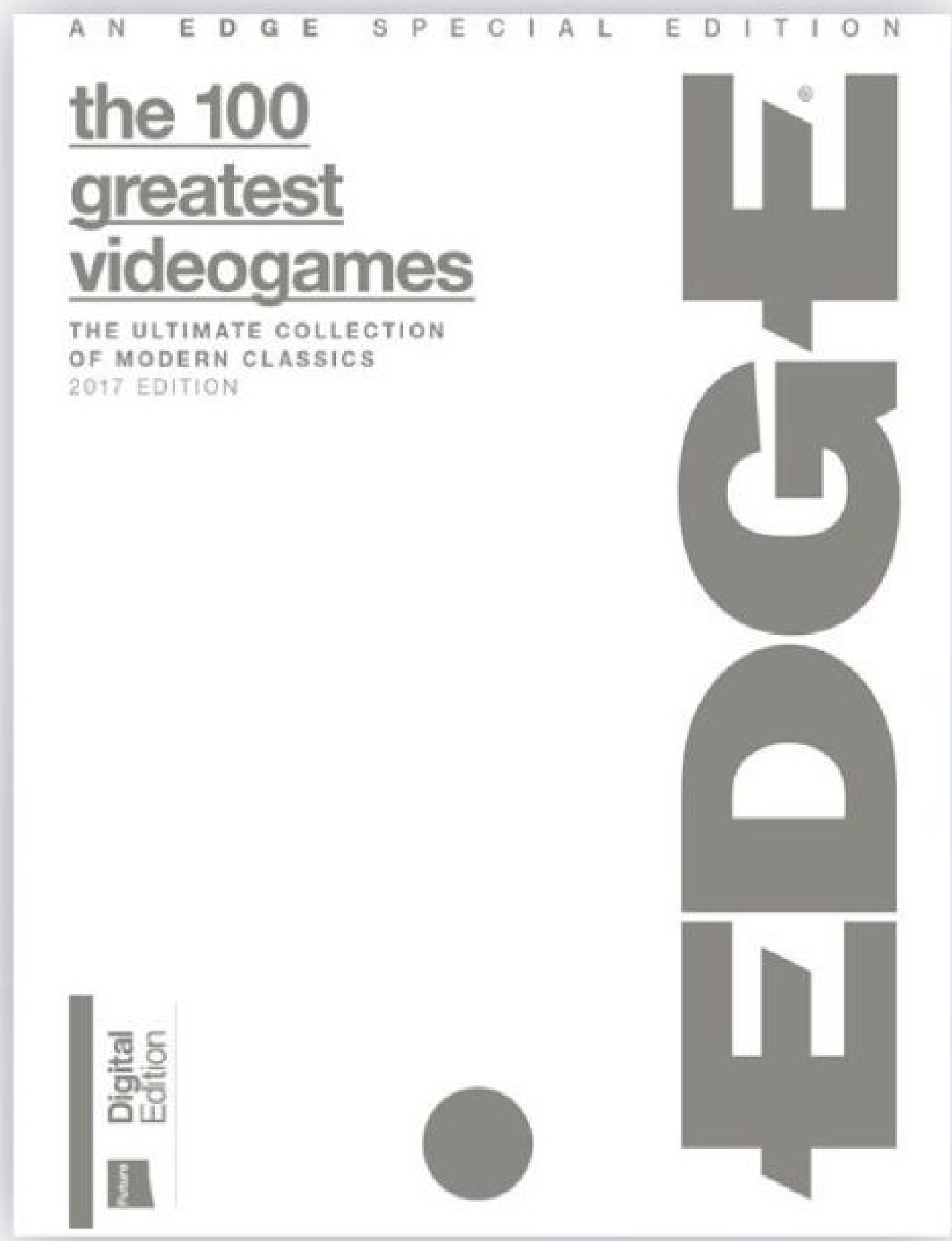

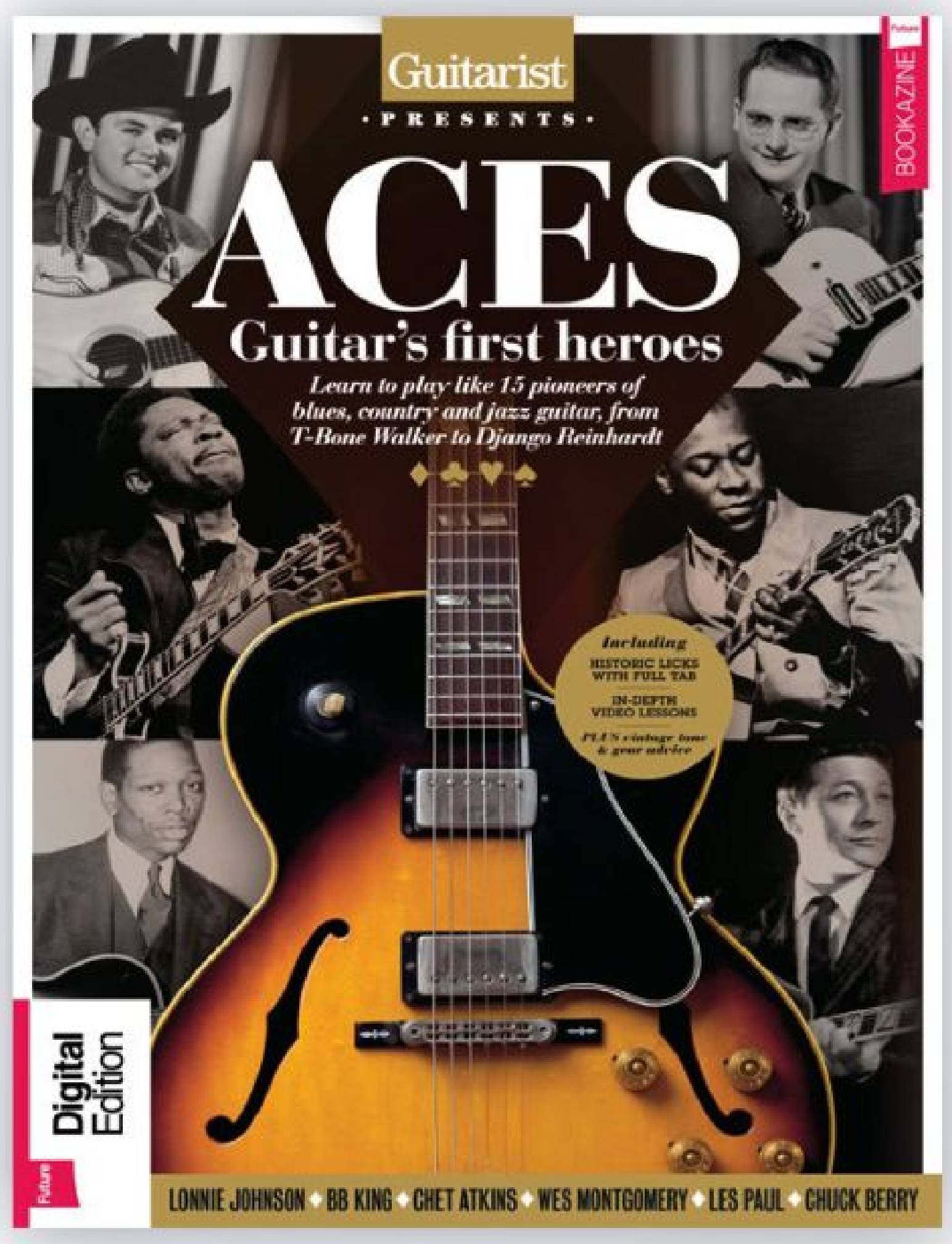

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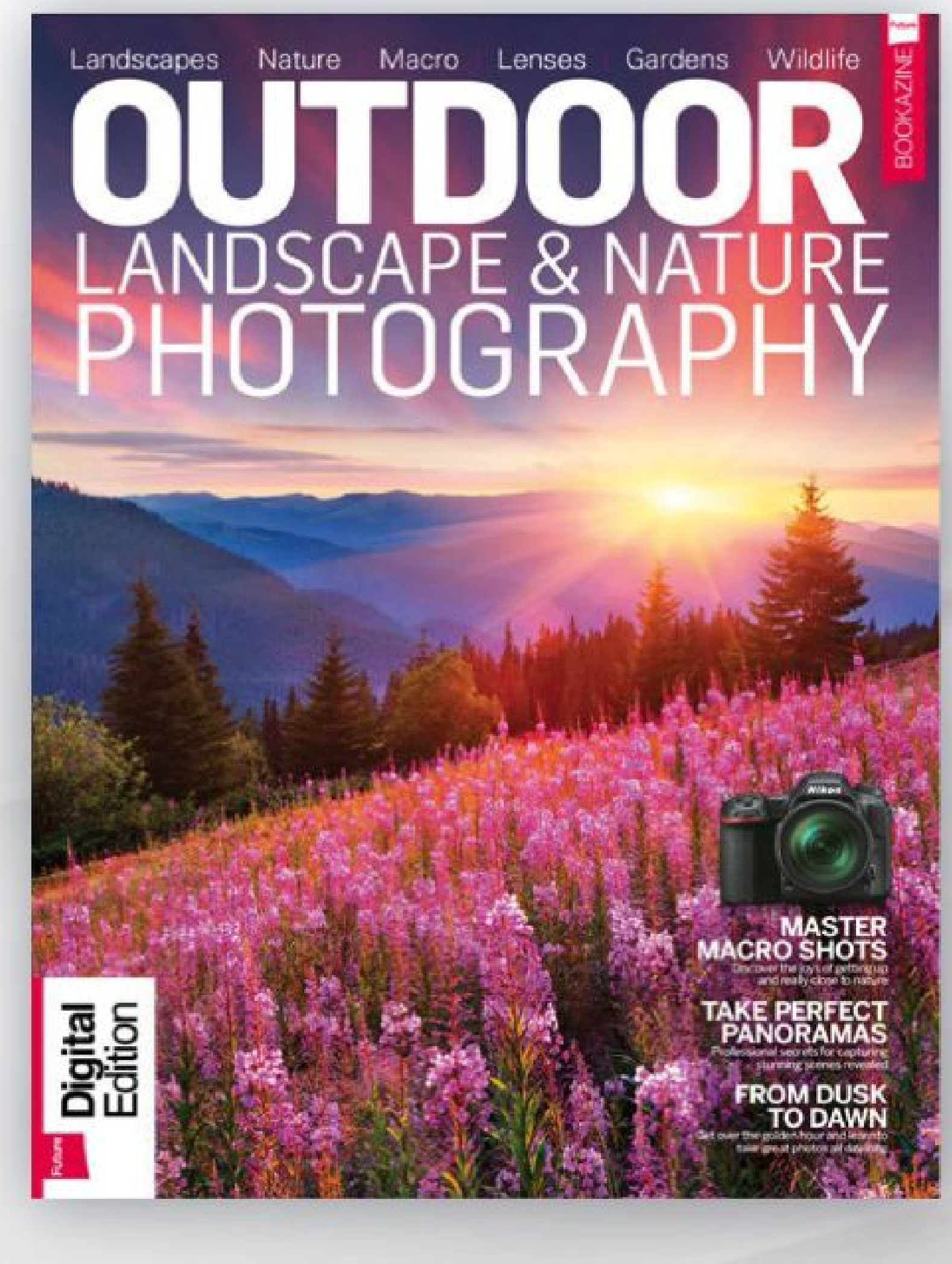

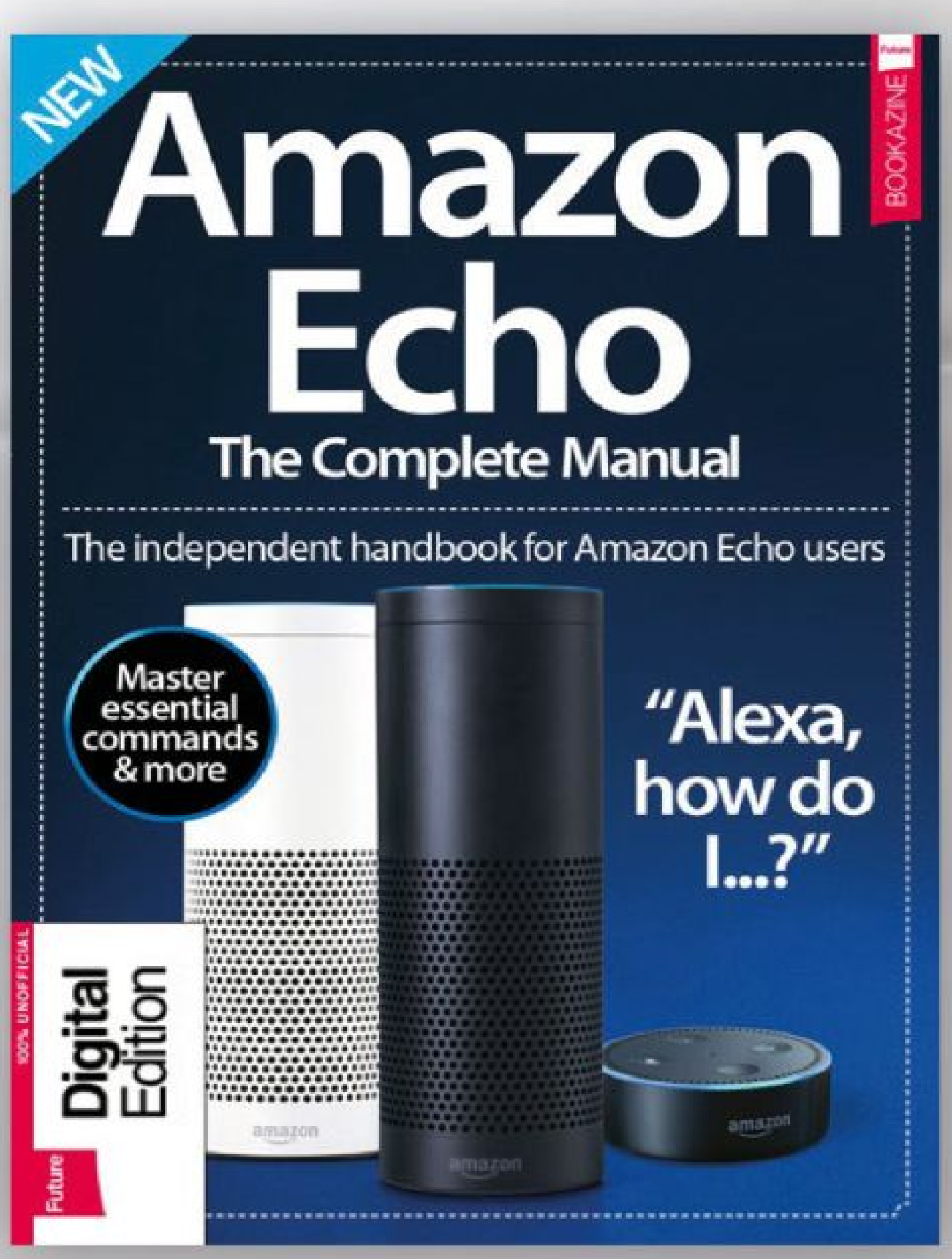

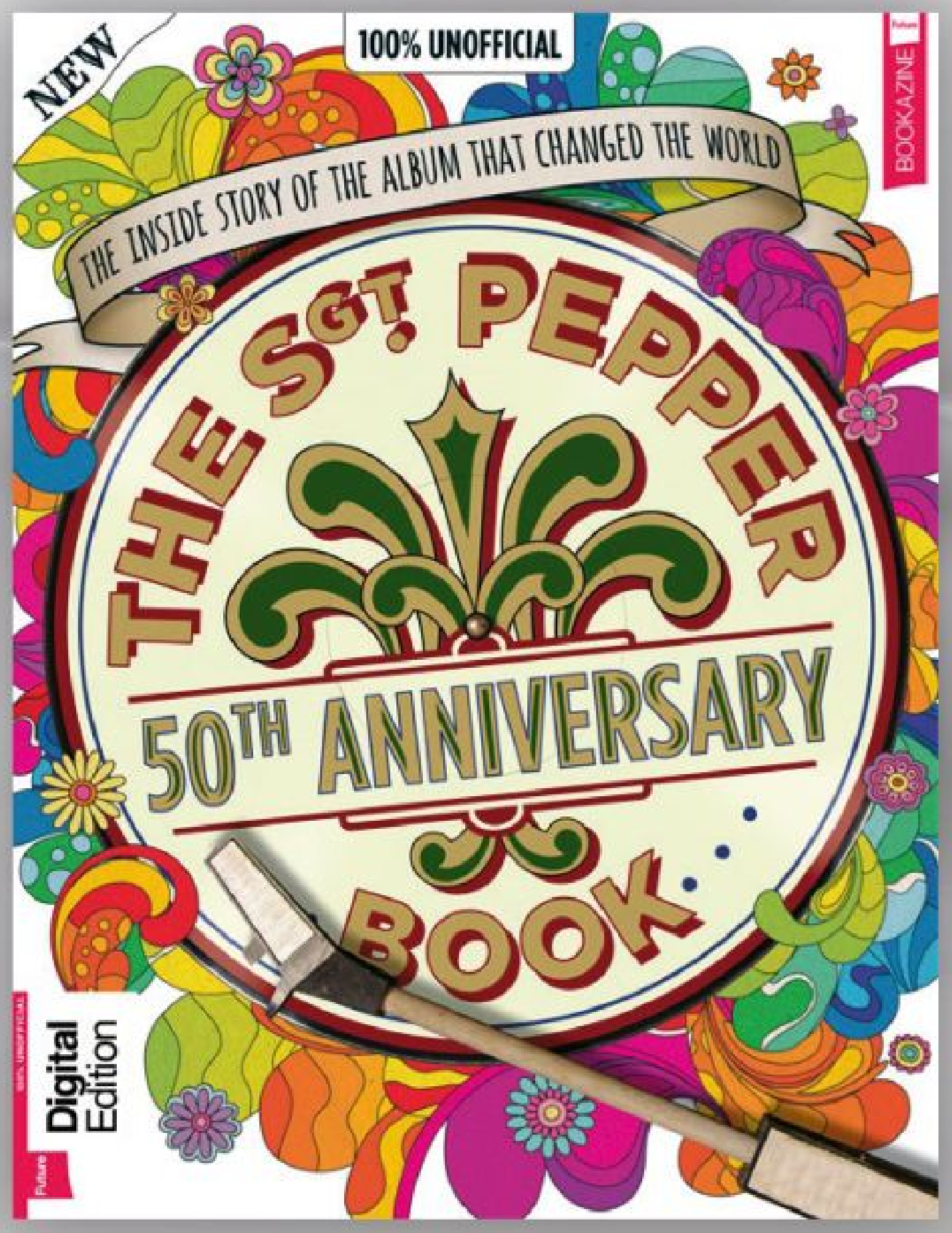

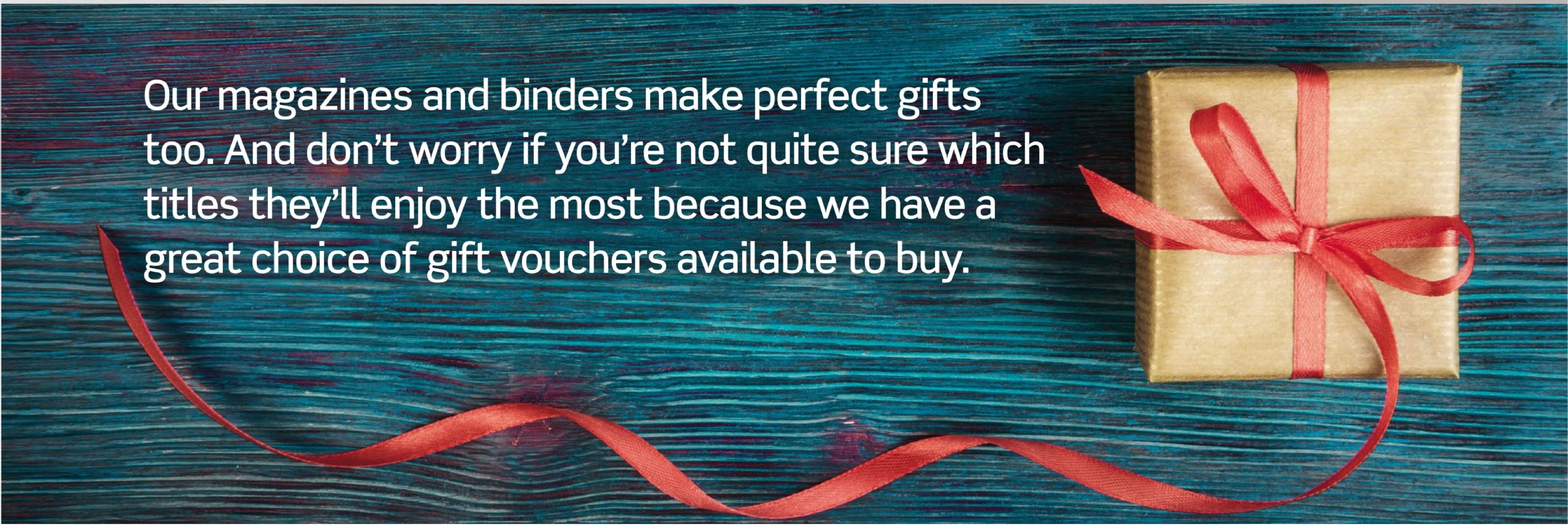

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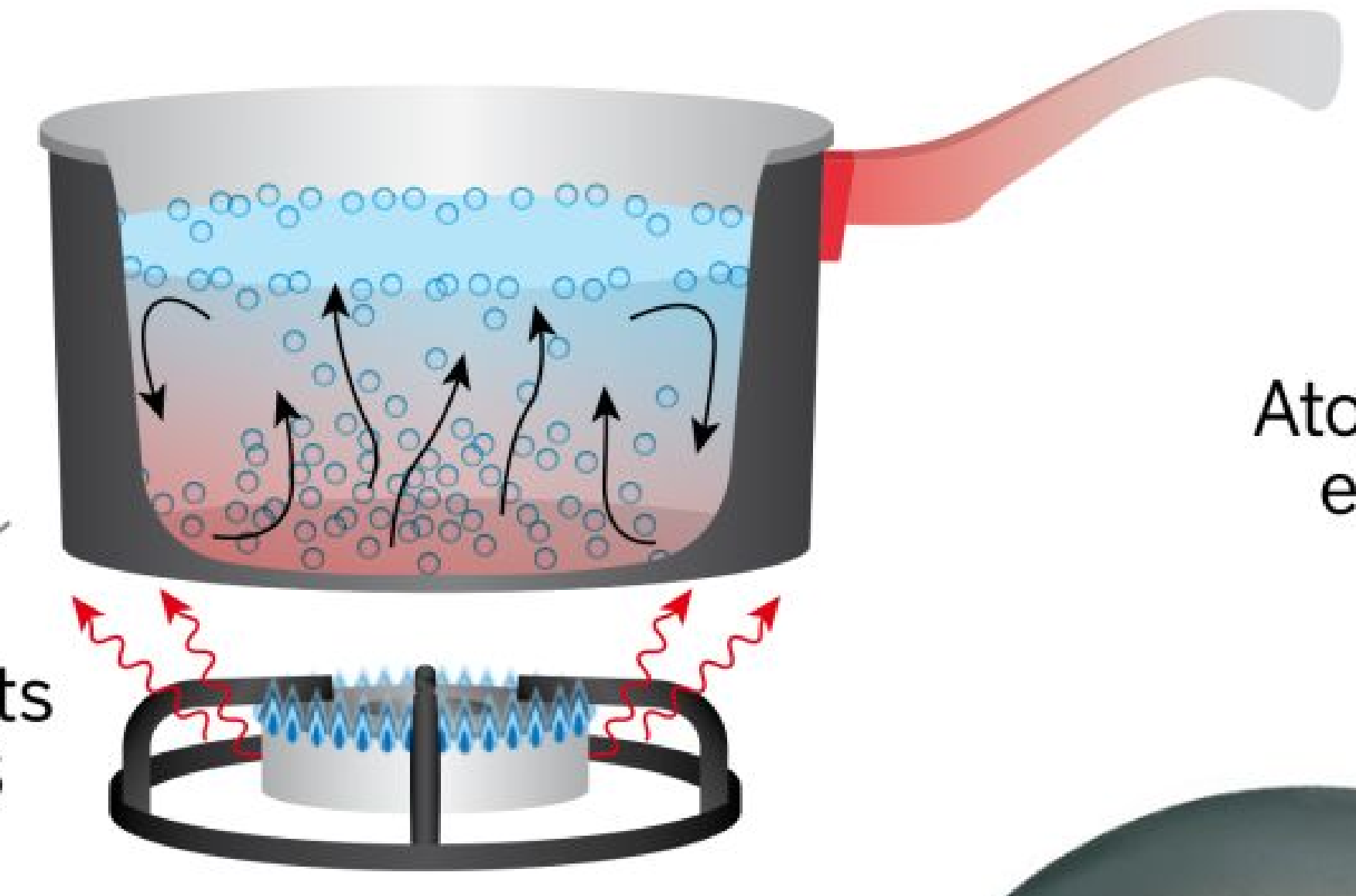

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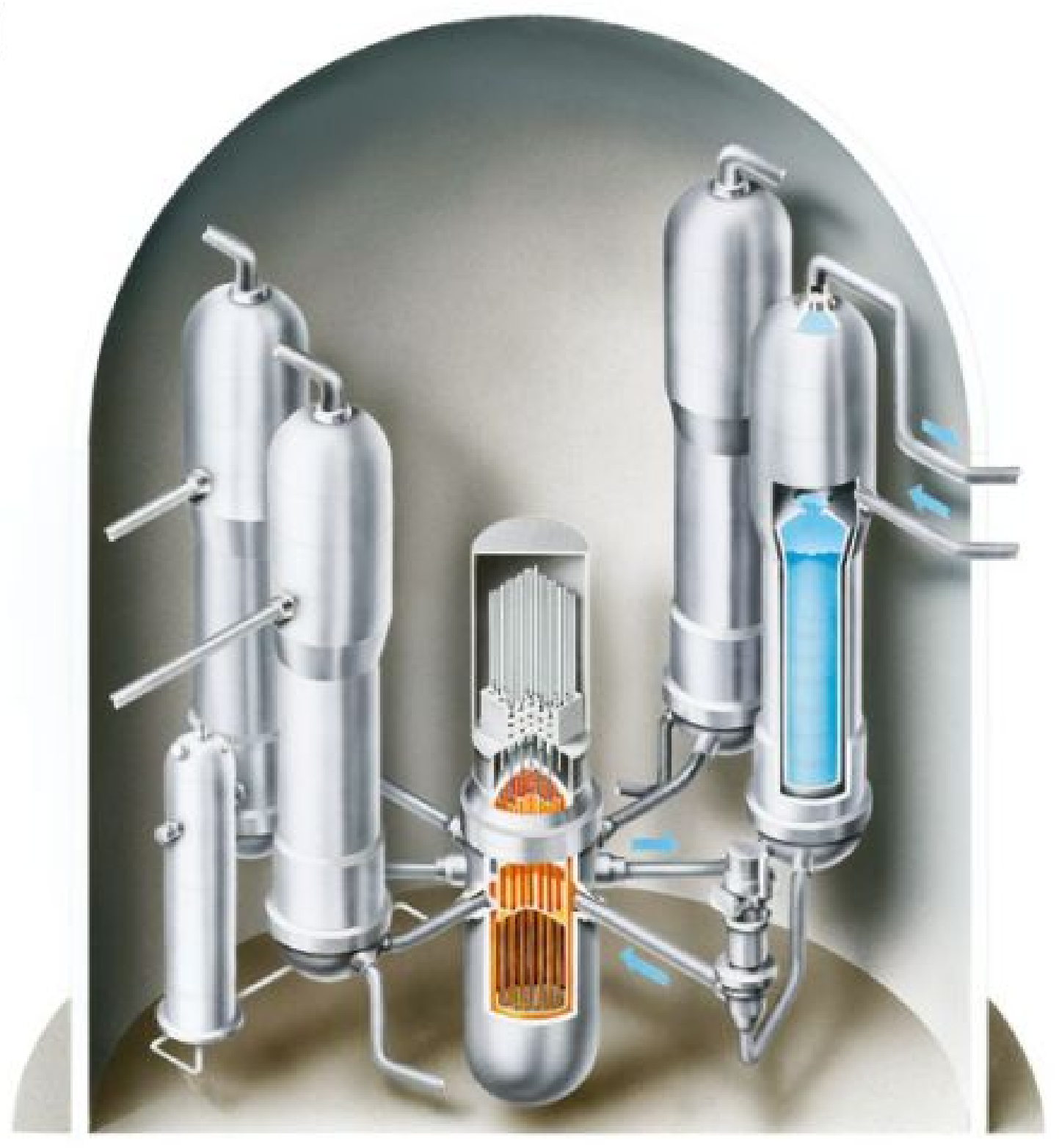

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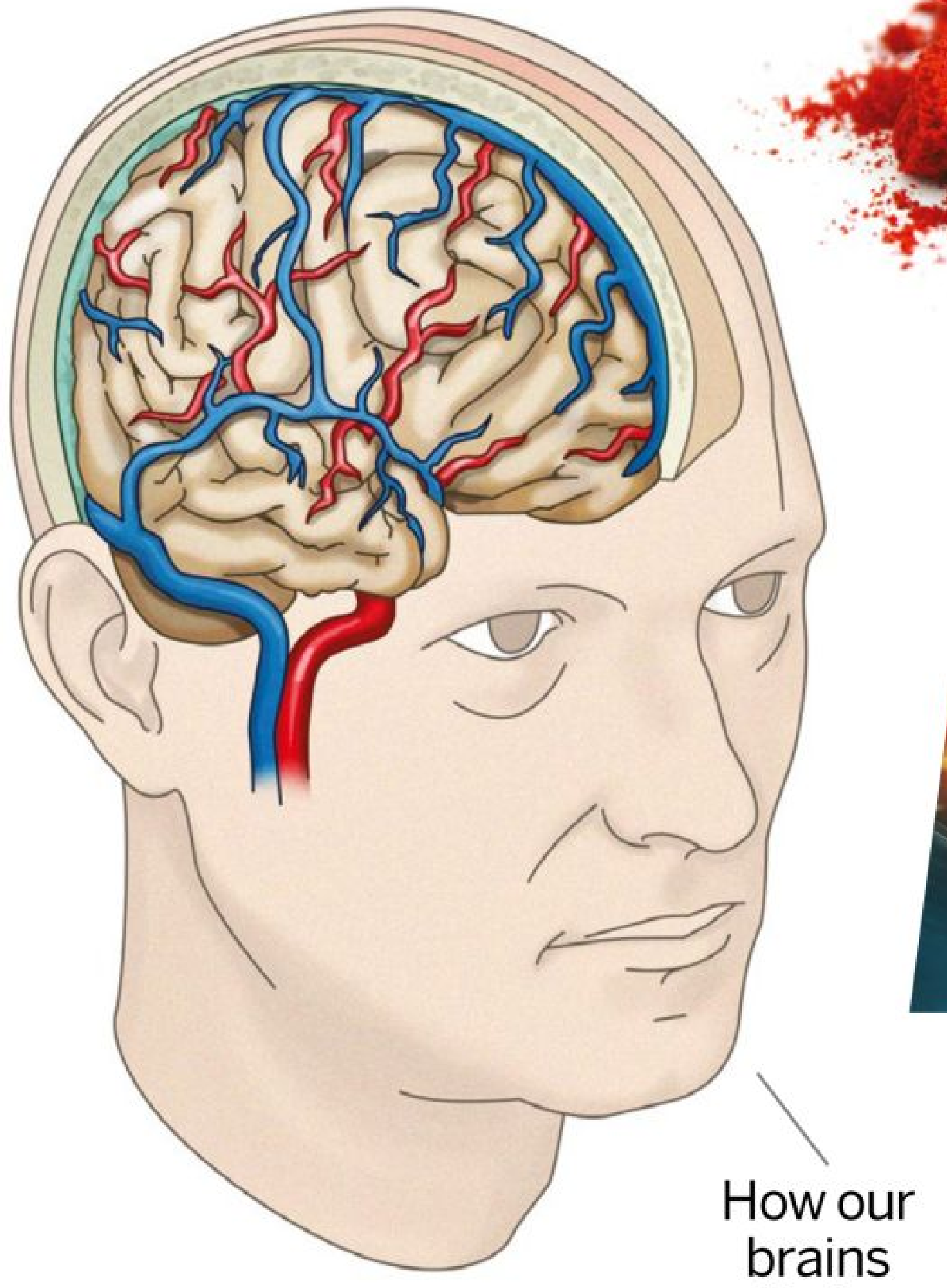

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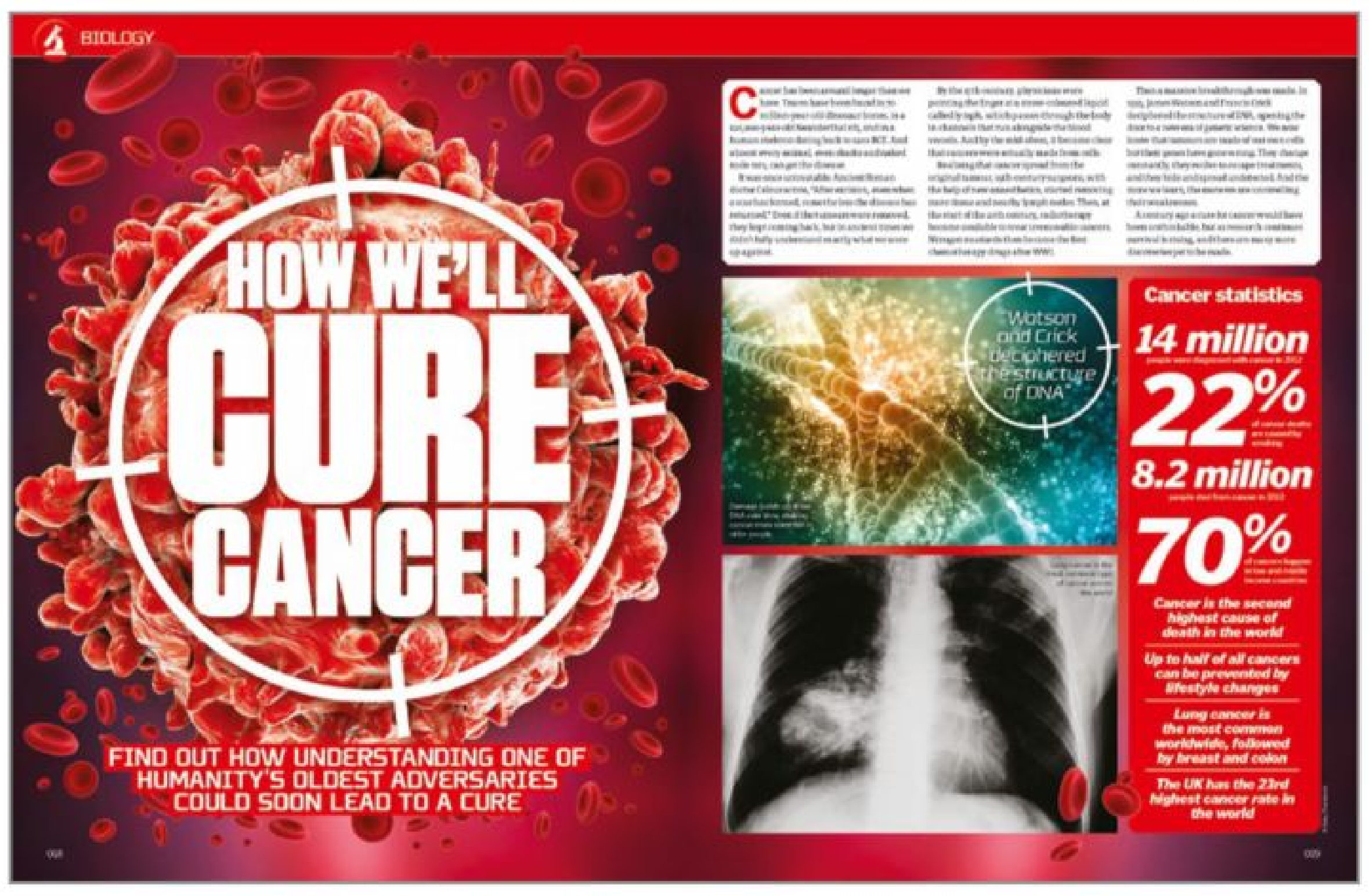

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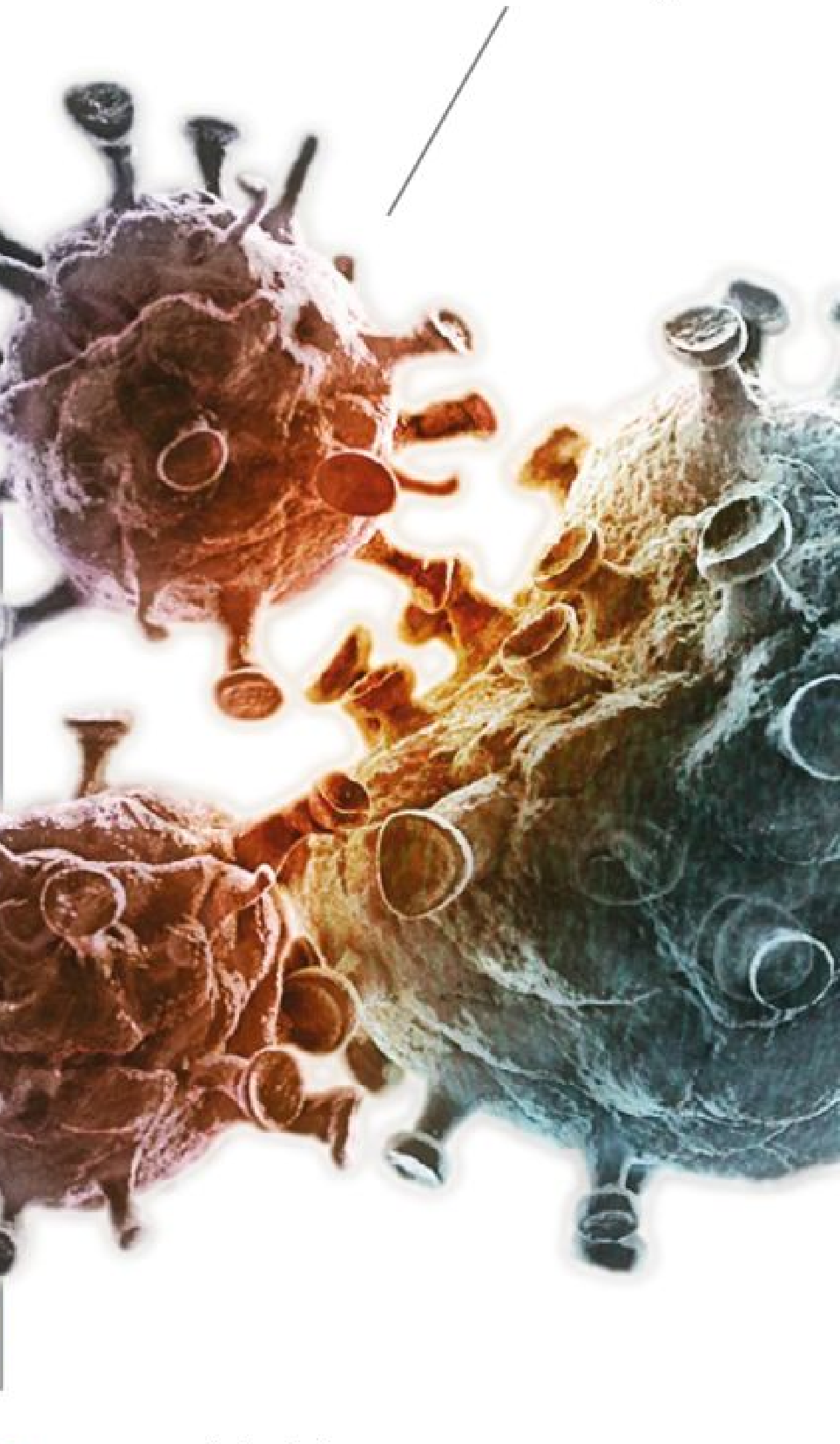

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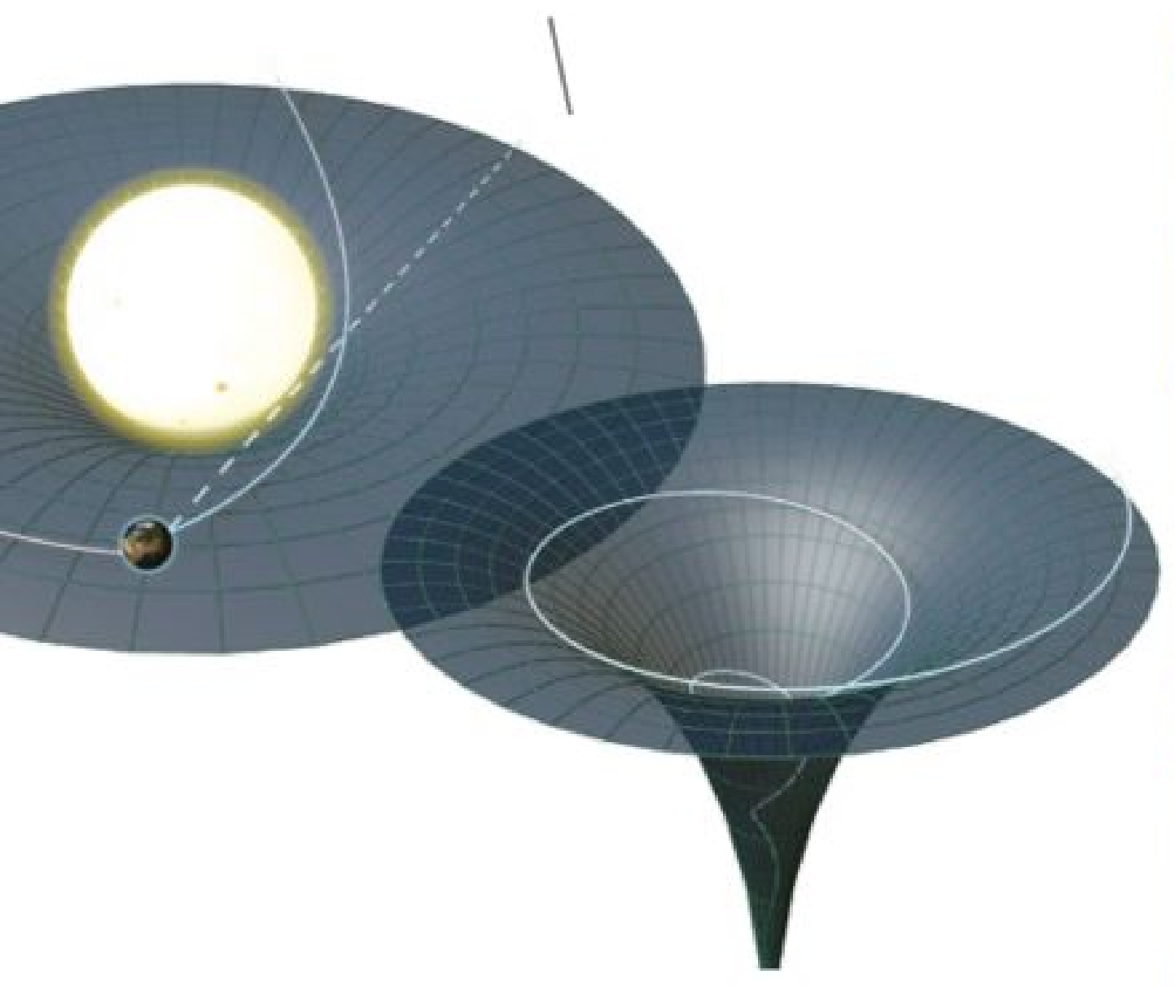

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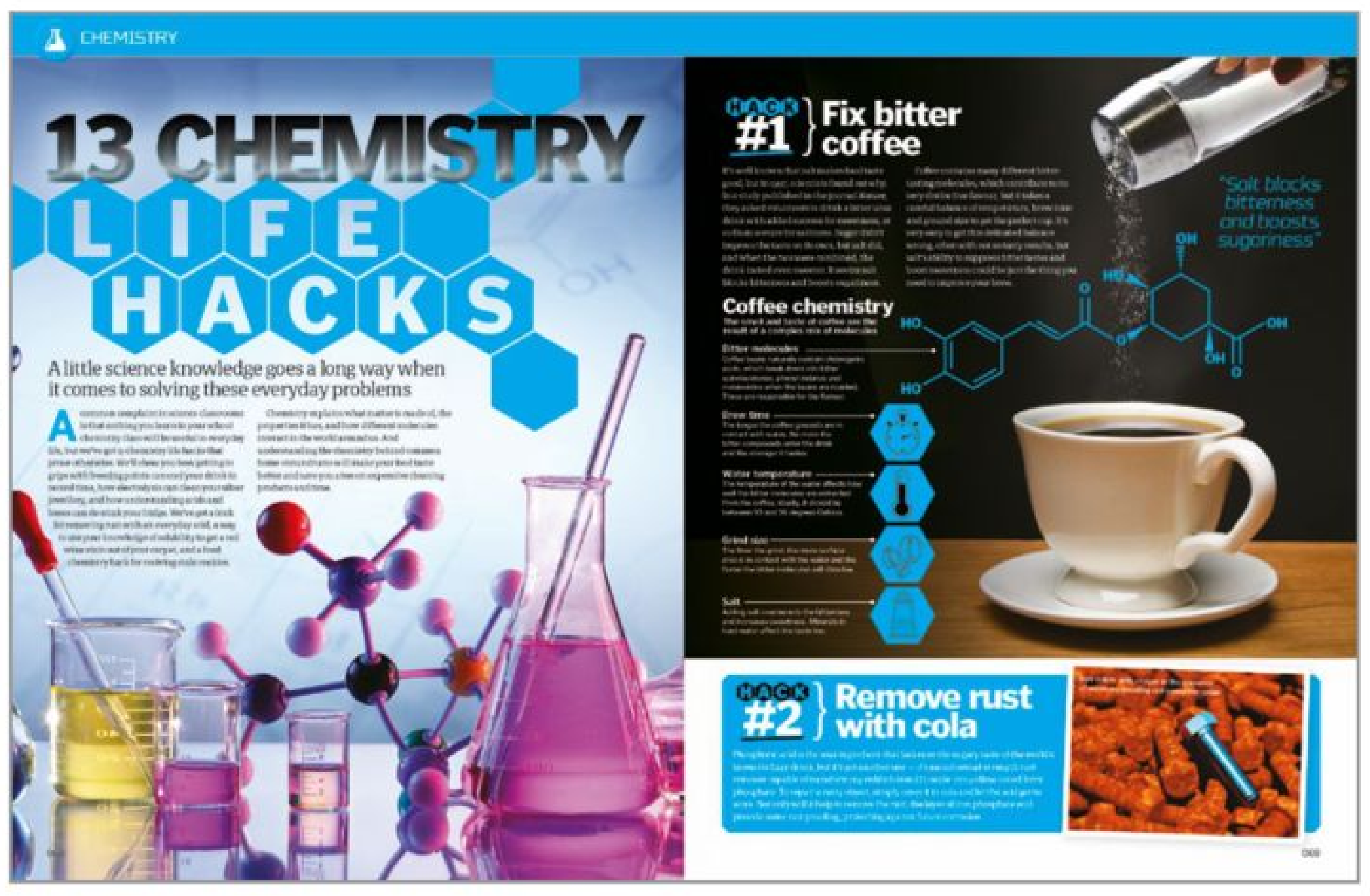

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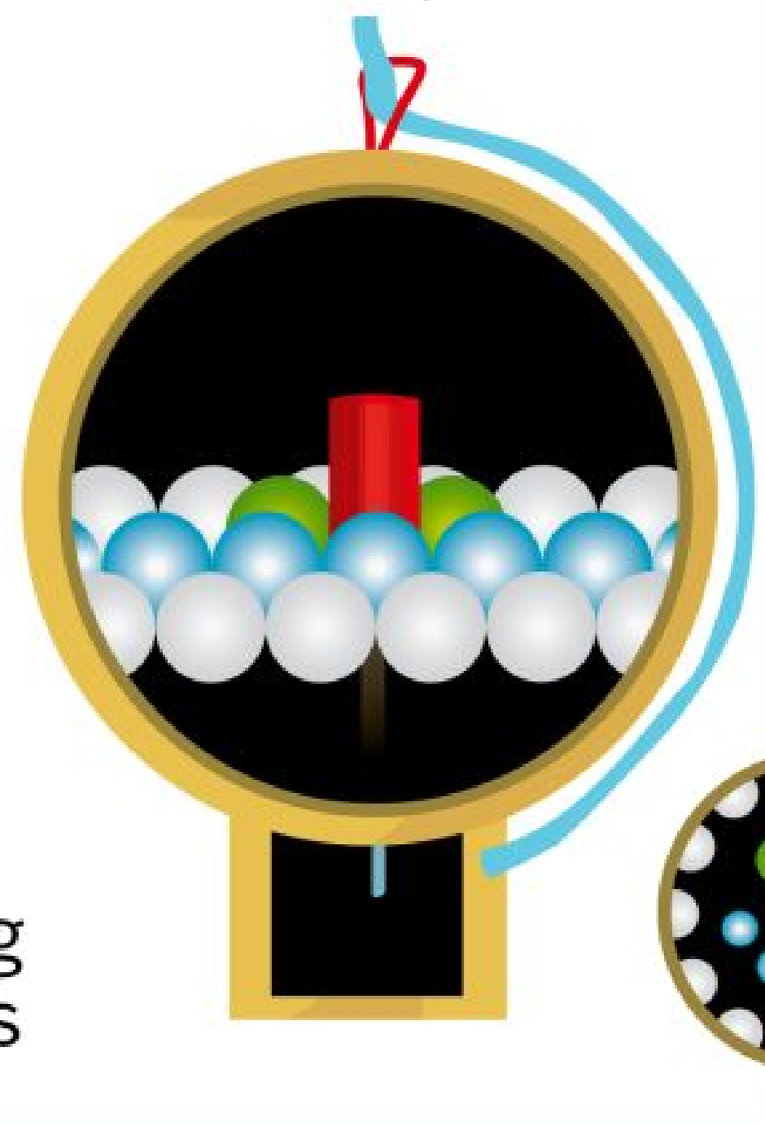

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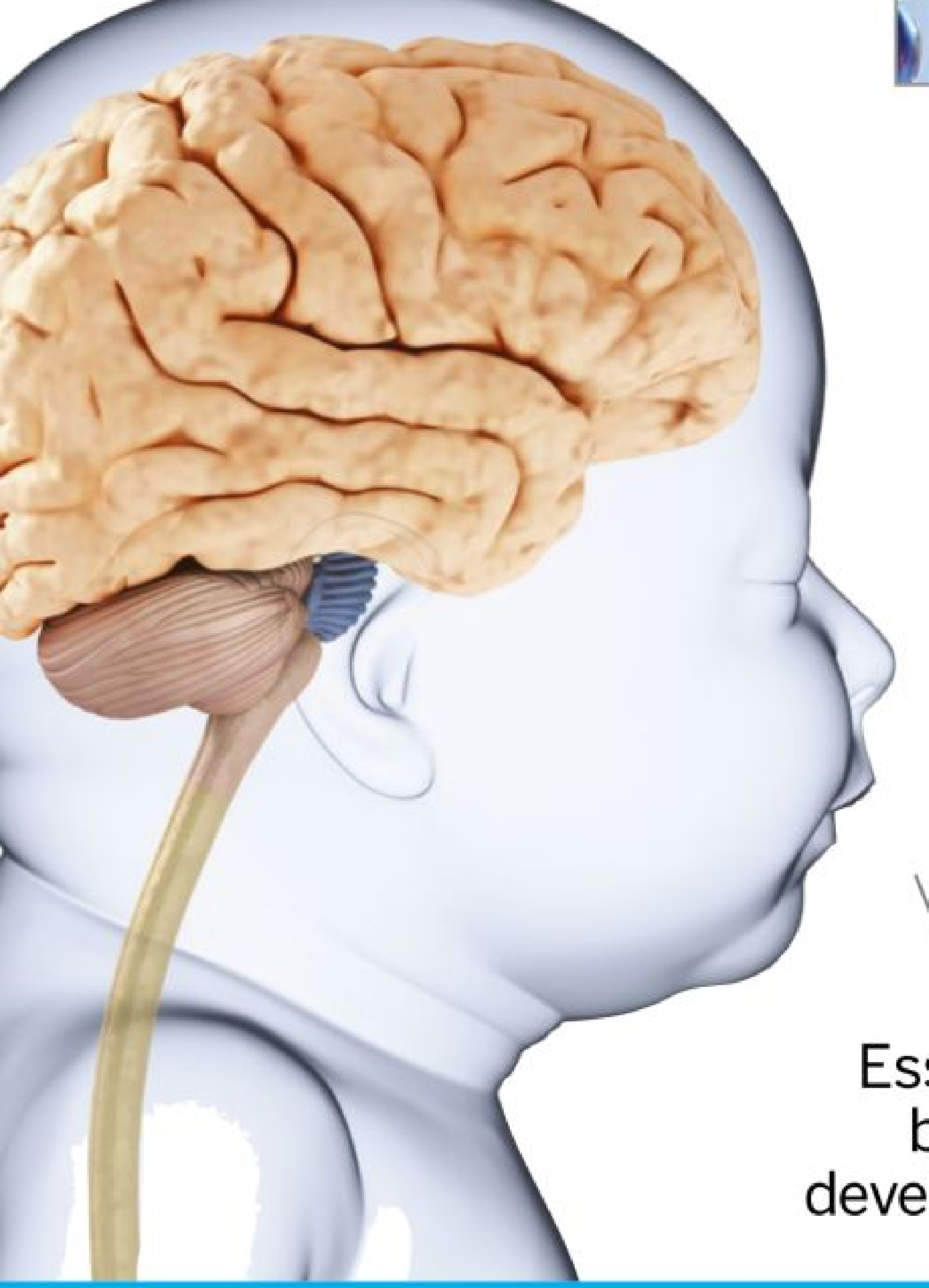

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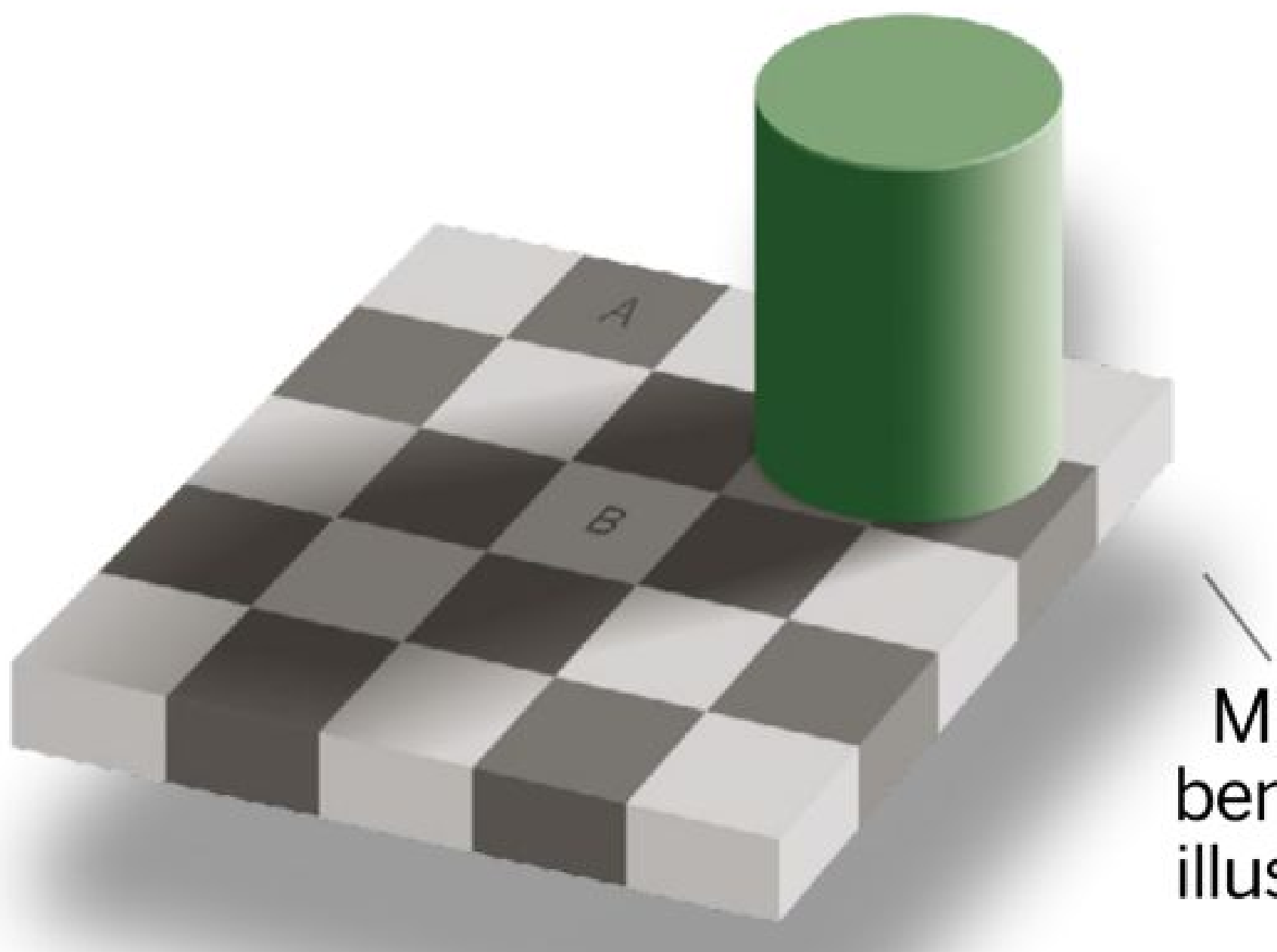

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